UNIVERSITÉ DE SHERBROOKE

École de Gestion

Industry 4.0: from strategic maturity models to operational deployment using lean six sigma tools

par

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Mémoire présenté à la faculté d'administration

en vue de l'obtention du grade de

Maître en Sciences, M. Sc.

Stratégie de l'intelligence d'affaires

Juin 2018

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Mémoire accepté le 19 juin 2018

SUMMARY

To remain competitive, companies must invest in emerging technologies that characterize the industry 4.0 (I4.0). To make the shift to I4.0, managers need to define their strategic direction and then deploy it to the operational level. The scientific literature presents few adequate responses to this need, focusing either at the strategic level or at the operational level separately. In particular, there are few approaches to manage the transformation at the operational level. Considering this gap in the literature, this research aims to develop a framework to guide managers in their decision-making towards digital transformation. Based on the Design Science methodology, we first performed a systematic literature review to identify approaches for the formulation of I4.0 strategies based on maturity models, as well as some tools to work at the operational level. At this level, we opted to work mainly with Lean Six Sigma (LSS)-based tools to support the implementation of I4.0, like the project charter and the value stream map (VSM) ,since it is an established standard in the manufacturing world, thus facilitating the transformation process for operations managers. Next, a new framework is proposed from these theoretical foundations combining LSS and Business Intelligence concepts, which were later tested in a real case study in a manufacturing company. Results suggest that the proposed approach has the potential to support managers in the I4.0 transformation process.

Key words: Industry 4.0, lean six-sigma tools, lean manufacturing, business intelligence, strategy deployment

RESUMÉ

Pour demeurer compétitives, les entreprises doivent investir dans les technologies émergentes qui caractérisent l'industrie 4.0 (I4.0). Pour apporter le changement vers l'I4.0, les gestionnaires doivent définir les orientations stratégiques et puis la déployer, au niveau opérationnel. La littérature scientifique présente peu de réponses adéquates à cette problématique, se concentrant soit au niveau stratégique, soit au niveau opérationnel séparément. Considérant cette lacune dans la littérature, cette recherche vise le développent d'un cadre conceptuel qui permet de guider les gestionnaires dans leur prise de décision de transformation numérique. La méthodologie adoptée a été fondée sur le « design science », composé de 5 étapes. La première est constituée d'une revue systématique de la littérature qui a permis d'identifier des outils utilisés pour la formulation des stratégies de l'I4.0 basés sur les modèles de maturité. Aussi, il a été possible d'identifier des outils sur le plan opérationnel, notamment, certains outils du Lean Six Sigma (LSS), comme le « project charter » et le « value stream map », pour soutenir la mise en œuvre de la I4.0, puisque le LSS c'est un standard établi dans le monde manufacturier, ce qui facilite le processus de transformation pour les responsables des opérations. Ensuite, un cadre conceptuel a été développé à partir de ces bases théoriques, en combinant des outils LSS et les concepts d´intelligence d'affaires, appliqués dans un cas réel auprès d'une entreprise manufacturière. Les résultats suggèrent que l'approche proposée a le potentiel de soutenir les gestionnaires dans le processus de transformation vers l'I4.0

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LIST OF ACRONYMS

BI	Business intelligence
DMAIC	Define, measure, analyse, improve
FMEA	Failure mode and effect analysis
IIoT	Industrial internet of things
I4.0	Industry 4.0
I4MM	Industry 4.0 maturity model
IoT	Internet of things
LM	Lean Manufacturing
LSS	Lean Six Sigma
M2M	Machine to machine communications
MESI	Ministry of economy, science and innovation
MRP	Materials resource planning
OEE	Overall equipment efficiency
PLC	Programmable logic controller
RFID	Radio frequency identification
SLR	Systematic literature review
SME	Small and medium enterprises
SS	Six sigma
TAM	Technology acceptance model
TPS	Toyota production system
VSM	Value stream mapping

ACKNOWLEDGMENTS

I would like to express my sincere gratitude to Professors Luis Antonio de Santa Eulalia and Elaine Mosconi for their inspiration and dedication that made it possible for this project to be realized. I would also like to thank the case study participants for their valuable contribution to this project. I also extend my appreciation to all the professors from the MSc Business administration, Business Intelligence, from Université de Sherbrooke, that made this journey possible.

Finally, I would like to thank my beloved wife and daughters, for being by my side in this adventure of living in another country. I would also like to thank my parents and sister, for their solid support, even though they were thousands of kilometres away.

"Look up at the stars and not down at your feet. Try to make sense of what you see, and wonder about what makes the universe exist. Be curious" – S. Hawking

1 INTRODUCTION

The first wave of industrial revolution (Industry 1.0) occurred at the end of the 18th century, with the first automated machines, via steam or water power. Industry 2.0 happened around 1870 with the concept of assembly lines, helped by electricity. Industry 3.0 began in 1969, with the first programmable logic controller (PLC) and the use of electronics and information technology in production automation (Deloitte, 2015).

The concept of Industry 4.0 (I4.0) emerged in the mechanical industry of Germany in 2011 (Lichtblau et al., 2015). In the United States, the term used is the Industrial Internet of Things (IIoT), which involves not only manufacturing, but also other industries, such as health care, civil construction, etc. Due to its importance at the international level, I4.0 was the subject of the World Economic Forum in 2016 (theme: The Fourth Industrial Revolution, what it means, how to respond) (Schuh et al., 2017). In Quebec, to deal with this phenomenon, the Government launched its "digital agenda", in 2016, and there is a ministry responsible for the digitization of the industries, the Ministry of Economy, Science and Innovation (MESI). An important program was also launched by the MESI in 2017, the "Manufacturier innovant" (in French), which encompasses high investments in the manufacturing sector to help companies quickly integrate emerging technologies from I4.0.

I4.0 can be defined as a phenomenon in which emerging technologies of physical, biological and digital worlds converge to revolutionize the organization of worldwide value chains, changing business models, production, distribution and consumption (Schwab, 2016). I4.0 is a phenomenon that is part of the Fourth Industrial Revolution transformations (Schwab, 2016). Another definition is a real-time network of people, equipment and objects used for business process management and for the creation of a value network (Dombrowski, Richter & Krenkel, 2017). It can also be defined as a “collective term for technologies and concepts of value chain organization” (Hermann, Pentek & Otto, 2016). Concerning the internal point of view of industry, or vertical perspective, it consists in the integration of industry’s physical objects with the Internet, called the digital world. If we consider a horizontal perspective, it relates to the application of these techniques throughout the whole company supply chain, as concerns the integration of data and objects from industry suppliers, logistics partners, service providers and customers (Deloitte, 2015).

In the manufacturing environment, the digitization concept can be unfolded in several dimensions, according to Figure 1, such as the smart factory, where machines can be equipped with sensors so that they can communicate with the company intranet/internet and also communicate with each other (machine to machine communication -M2M). Another dimension is smart operations, which consists of digital information sharing internally and externally with the company, usage of cloud to store and analyze information, autonomous processes that self-react to the production environment (Lichtblau et al., 2015). The third dimension is smart products, which stands for installing sensors in the product that allow data collection in customer operations, providing new opportunities for the company to offer services integrated to the product, such as preventive maintenance, product usage analysis (Kolberg, D., Zühlke, D., Zuehlke, D., 2015). Finally, the fourth dimension is data-driven services, enabled by the smart products infrastructure, where the company can change its business models, creating value through product data analysis, adding digital services to customers (Rymaszewska, Helo & Gunasekaran, 2015).

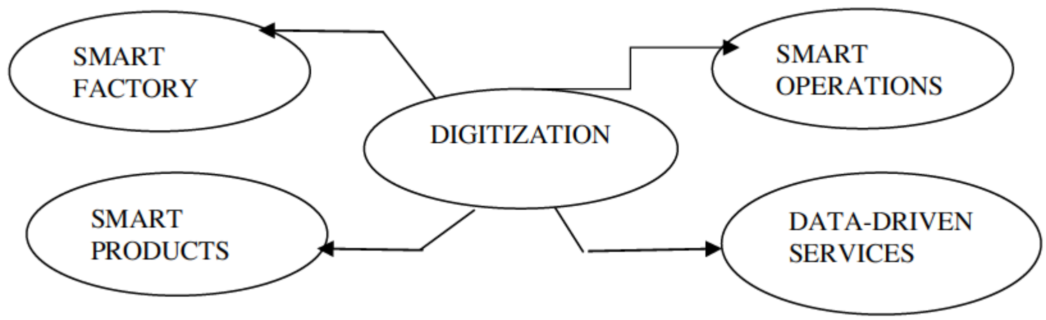

Figure 1 - I4.0 Digitization process dimensions, adapted from Lichtblau et al. (2015)

Research problem

In an I4.0 strategy transformation, there are breaking changes (worthy of an industrial revolution) and also continuous improvements. To make these changes, companies must first identify their strategic orientation and then deploy it to the operational level. It is fundamental to make this strategic orientation of I4.0 so that the company can identify its current and desired situation towards I4.0. This strategy orientation can lead to a change in the business model, adding data-driven services that can provide new sources of revenue. The access of a large quantity of data from smart products makes value creating possible while generating profit (Rymaszewska et al., 2015). I4.0 can enable the application of the Product Service System, "where companies develop products with value-added services, instead of a single product itself and provide their customers with needed services (Lee, Kao & Yang, 2014). Moreover, the connection between I4.0 strategy and the operational level will provide company management with important information, such as the productivity gains after I4.0 implementation, quality improvement and so forth.

It is at the operational level that gaps have been identified in the literature, since there are just a few frameworks at the strategic level and no framework making explicit connection to the operational level. At the strategic level, we find mainly tools for evaluating maturity levels, such as the IMPULS framework ("impulse" in German) (Lichtblau et al., 2015). IMPULS is a maturity model, which is a collection of organized elements that define the characteristics of effective processes at various stages of development (Pullen, 2007). Another example is the conceptual framework of Erol et al. to formulate the strategy of companies towards I4.0 (Erol, Schumacher & Sihn, 2016).

As for the operational level, the literature is limited, but some suggestions exist on how to deploy strategy at the operational level. At this level, there are some works about Lean Manufacturing (LM) and Six Sigma (SS), presented as a possible solution for this problem (Meudt, Metternich & Abele, 2017). LM is intended to produce products and services at lowest cost and at the time required by the client, while eliminating/reducing waste in the process. Six Sigma aims to reduce the variation of the process, using the approach DMAIC (Define, Measure, Analyze, Improve, Control). Among the various methods of process continuous improvement, SS and LM are considered among the best methodologies, widely used in various industries. They are currently designated as the state of the art of continuous improvement (Salah, Rahim & Carretero, 2010).

However, to the best of our knowledge, two major gaps exist: no framework exists to connect the strategic level to the operational level; and the proposed tools at the operational level do not respond to the data-driven needs for smart factories and smart operations. Thus, this work aims to contribute to reducing this gap and its objectives are stated in the following.

Research objective

This research has the following objectives:

1. identify the LSS tools that can help to translate the strategic I4.0 objectives at the operational level;
2. check if these LSS tools need adaptation to the context of I4.0;
3. propose adjustments consistent with an I4.0 migration strategy, as appropriate;
4. assess the contribution of the LSS tools in an organizational context of transformation towards I4.0.

In order to achieve the overall objectives, the research question that this study seeks to answer is: What would the roadmap be to translate the I4.0 strategy into concrete projects on the shop floor, for companies that are in an I4.0 transformation process?

2 BACKGROUND

In this chapter, we present the fundamental concepts of this research.

2.1 Industry 4.0 principles

According to the literature, the principles of I4.0 are: interconnection, information transparency, decentralized decisions, technical assistance. The principle of interconnection is the connection of machines, equipment, sensors, operators between them, but also the connection of all these elements to the cloud. These communications standards and cybersecurity are also part of this principle. Information transparency contains analyses of the data and the provision of information to users. It is a virtual copy of the physical world, created through the binding of data sensors with factory digitized models. Decentralized decisions allow the use of computers, sensors and operators to monitor and control the physical world, in an autonomous manner. Technical assistance is the automation of physical and virtual operations (Hermann et al., 2016). As the definition of I4.0 is complex, and may contain different definitions depending on the stages of the company on this topic, several models of maturity have been created to help companies to position themselves on this theme.

2.1.1 Industry 4.0 strategy framework

A framework concerning I4.0 vision and strategy building was proposed by (Erol, Schumacher & Sihn, 2016). Its main goal was to help companies develop their I4.0 objectives and clearly communicate them to its stakeholders. It consists of three phases, as described below:

Envision – This phase concerns the company understanding of I4.0 concepts and the alignment of these concepts with company-specific objectives and customer needs. The stakeholders for this phase are company top management, and may involve other important business partners and middle management, customers and external experts of I4.0.

Enable – This phase turns the vision defined in the envision phase into concrete actions, transforming it into a strategic plan; so it describes what has to be done to achieve these objectives. These concrete actions are represented in four layers: Customer segments (market perspective, value proposition (product perspective), key resources, technologies and activities (process perspective) and the necessary partners (the network perspective).

Enact - This phase transforms the strategic plan defined at the Enable phase into concrete projects, with a timing chart, defined teams and resources.

2.2 Maturity model and readiness definition

The word maturity has the following definitions: "state of being complete, perfect, or ready" and indicates some advancement in the development of a system. Therefore, maturing systems (e.g. biological, organizational or technological) raise their abilities over time concerning the accomplishment of some wanted future state (Schumacher, Erol & Sihn, 2016).

According to Wendler, (2012) "a clear definition of the term maturity model is often avoided. Publications of maturity models rather use descriptions of purpose and functioning of the models". Maturity models generally consist of a sequence of levels (or stages) that form a projected, wanted, or logical track from an initial state of maturity. Maturity models are used to evaluate as-is situations, to guide improvement initiatives, and to control evolution (Maximilian Röglinger, Jens Pöppelbuß, Jörg Becker, Maximilian Roeglinger, Jens Poeppelbuss, 2012). Maturity models propose to organizations a simple but effective opportunity to evaluate the quality of their processes. Developed out of software engineering, the application fields have expanded and maturity model research is gaining more importance (Wendler, 2012).

Maturity models define the progress of an entity over time. This entity can be anything of interest: a human being, an organizational function, etc. (Gabor, 2001). A maturity model is an organized collection of elements that defines the characteristics of effective processes at diverse stages of development. It also proposes points of separation between stages and methods of transitioning from one stage to another'' (Pullen, 2007). ``A maturity model consists of a sequence of maturity levels for a class of objects. It represents an anticipated, desired, or typical evolution path of these objects shaped as discrete stages. Typically, these objects are organizations or processes.'' (Becker, Knackstedt & Pöppelbuß, 2009).

A synonym for maturity model is readiness models with the aim of capturing the starting point and preparing the development process. Readiness assessment occurs before engaging in the maturing process. In the production area, recent readiness and maturity models have been used for example in eco-design, and utility management energy manufacturing or lean manufacturing (Schumacher et al., 2016).

2.3 IMPULS – Industry 4.0 readiness

This model was created by the German institutions: VDMA, RWTH Aachen, IW Consult. The design of this maturity model was performed using a mixed methodology of an analysis of the literature, expertise, workshops, and a comprehensive company survey. The study defined six readiness levels: 0-Outsider; 1- Beginner; 2- Intermediate; 3- Experienced; 4- Expert; 5 -Top performers. The Readiness Model is founded on the four dimensions of Industry 4.0 (Smart factory, Smart operations, Smart products, Data-driven services. The model identified two additional, commonly appropriated dimensions that were also taken into account: strategy and organization, and employees. All in all, the model then looks at six dimensions: Strategy and organization, Smart factory, Smart operations, Smart products, Data-driven services and Employees. Figure 2 delivers an outline of the structure of the Readiness Model. It shows the six basic dimensions. The table 1 shows the fields related with each of the six dimensions (Lichtblau et al., 2015).

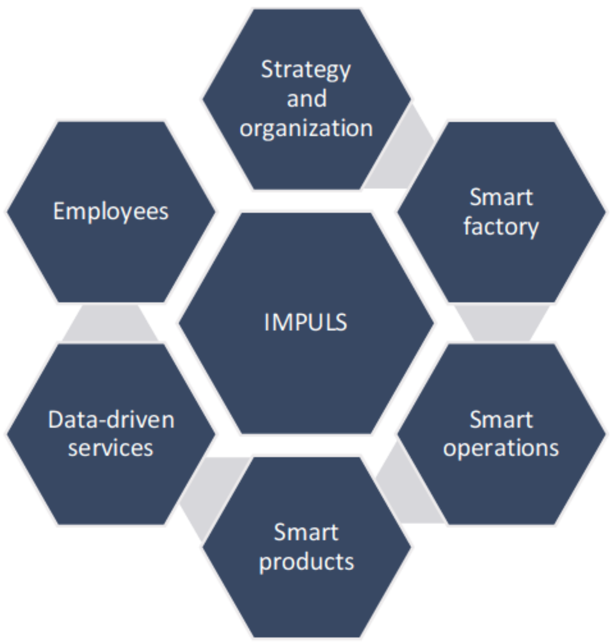

Figure 2 – IMPULS dimensions, Lichtblau et al. (2015)

Table 1 : IMPULS dimensions and related fields

IMPULS Dimensions	**IMPULS Fields**
Strategy and organization	Strategy
	Investments
	Innovation management
Smart Factory	Digital modelling
	Equipment infrastructure
	Data usage
	IT Systems
Smart operations	Cloud usage
	IT security
	Autonomous processes
	Information sharing
Smart products	Data analytics in usage phase
	ICT add-on functionalities
Data-driven services	Data-driven services
	Share of revenues
	Share of data used
Employees	Skill acquisition
	Employee skill sets

Lichtblau et al. (2015)

2.3.1 IMPULS – Smart operations

Smart operations concerns the degree of autonomous processes, the degree of information sharing with other processes (Horizontal and Vertical Integration) and IT security and cloud usage. Horizontal means the integration of all internal and external actors in a value chain, from suppliers, internal production, to customers. Vertical integration stands for integration only inside the company, from product development to planning, production, after sales, finance, marketing, etc. (Lichtblau et al., 2015). Autonomous processes stand for the workpieces moving by themselves to the next processing station, the establishing of process sequences by their own, and the communication of production parameters to the equipment (Lichtblau et al., 2015). “Autonomy in general means the independence of a system in making decisions by itself without external instructions and performing actions by itself without external forces”. “Autonomy of a system means two basic characteristics: First, independence from neighbour systems and from its environment, and second, the ability to control itself”. The combination of autonomous resources (cells, robots, transport systems) with autonomous parts, subassemblies and products will drive to autonomous processes (Scholz-Reiter & Freitag, 2007).

2.3.2 IMPULS - Smart factory

Regarding the smart factory, the equipment infrastructure checks if the pieces of equipment are able to communicate with each other, i.e. machine to machine communication (M2M), are interoperable and can be controlled. M2M happens between machines (some objects or devices) with computing/communication capabilities without human intervention. M2M uses the machines to monitor certain events with sensors and to instruct actuation. The captured data are relayed through wired or wireless networks to servers, which extract and process the information gathered and automatically control and instruct other machines (Kim, Lee, Kim & Yun, 2014). The logic concerning M2M communications is based on three factors: 1) a networked machine is more valuable than an isolated one, 2) when multiple machines are interconnected, more autonomous applications can be achieved, and 3) smart and ubiquitous services can be enabled by machine-type devices intelligently communicating with other devices anytime and anywhere (Chen, Wan, Gonzalez, Liao & Leung, 2014).

2.3.2.1 Data Collection and Usage (Business intelligence concepts)

The smart factory presents the items of data collection and data usage. To explain the theory that supports these data items, we can refer to the Business Intelligence (BI) concept. The BI can be defined as: “A combination of processes, policies, culture, and technologies for gathering, manipulating, storing, and analyzing data collected from internal and external sources, in order to communicate information, create knowledge, and inform decision-making” (Foley & Guillemette, 2010).

According to Foley et al. (2010) the BI can be viewed as a process. The first phase is data collection, where the type of data to be collected is identified, for example, the setup time or manufacturing time, and the frequency of this data collection. The second phase is data storage, which could be in a digital (relational database, spreadsheets, data warehouses) or paper form. After the data is stored there should be a critical analysis of its quality. Data quality has several dimensions, such as accuracy, timeliness, precision, reliability, currency, completeness, and relevancy (Wang & Strong, 1996). The third phase is data visualization, which could be in the form of reports and/or dashboards. Dashboards are visual and interactive tools that allow users to watch relevant performance indicators for the company. Dashboard information helps users in their decision process to achieve company goals (Maddah, 2013). The fourth phase is analysis, which stands for applying statistical methods and/or computational tools to discover relevant patterns in the business. The analysis can be descriptive, predictive and prescriptive. Descriptive analytics finds patterns and relationships in historical and existing data (Haas, Selinger & Tan, 2011). Predictive analytics embraces a diversity of techniques, such as regression, neural networks, etc., that predict future results based on historical and current data (Gandomi & Haider, 2015). The final phase is prescriptive analytics, that has a “what if” capability, it suggests actions to different scenarios (Chae & Olson, 2013)

2.3.3 IMPULS – Strategy and organization

Strategy and organization is organized in three sub dimensions: Strategy, investments, and innovation management. Strategy verifies if there is a strategy to implement I4.0, and if it´s embedded in the overall strategy of the company. If there is an I4.0 strategy, it should have a system of indicators to track it, and the strategy should be revised in a defined frequency. Investments stand for planned investments that should be made in the company, so that it can progress in the I4.0 transformation. Innovation management specifies that the company has to innovate in its management/business practices, enabling new business models, such as new services incorporated in its products (Lichtblau et al., 2015)

2.3.4 IMPULS – Smart products

This dimension relates to the technologies incorporated into the products, such as sensors, that will allow the company to analyze product data on the field, opening possibilities to provide new services to customers, and also to have predictive models, in order to reduce the product failure rate on the field.

2.3.5 IMPULS – Data driven services

The smart products technologies allow companies to offer new services to its customers, based upon data analysis coming from product usage. This dimension checks if data-driven services are available at the company, the percentage of the revenues generated by them, and if this data is shared throughout the company, and with its customers.

2.3.6 IMPULS – Employees

I4.0 presents new challenges to employees, because they must acquire new qualifications in order to be able to work with its new technologies and processes. This dimension allows checking whether there is a definition of I4.0 skills, and if these skills are assessed and implemented.

2.4 Lean Six Sigma (LSS)

LSS is the integration between the methodologies of Lean Manufacturing (LM) and Six Sigma (SS). LM is intended to produce products and services at lowest cost and at the time required by the client, while eliminating/reducing waste in the process. SS is aimed at reducing the variation of the process, using the DMAIC (Define, Measure, Analyze, Improve, Control) approach. Among the various methods of process continuous improvement, SS and LM are considered among the best methodologies, widely used in various industries. They are now known as the state of the art of continuous improvement (Salah, Rahim & Carretero, 2010)

2.4.1 Lean Manufacturing (LM)

The aim of (LM) is to be very responsive to customer demand via waste reduction. The LM goal is to produce products and services at lowest cost and at a time required by the customer. The lean concept was created in Japan after the Second World War when Japanese manufacturers understood their lack of capacity to invest in the rebuilding of the damaged facilities. Japanese car manufacturers, like Toyota, produced cars with fewer resources, such as: inventory, human effort, investment, and defects and introduced a greater and ever-growing variety of products. LM gives companies a competitive advantage via cost reduction, productivity improvement and quality (Bhamu & Singh Sangwan, 2014).

The term LM was created in the International Motor Vehicle Programme by researchers of the Massachusetts Institute of Technology, with the goal of understanding the performance gap between American and Japanese car manufacturers. Womack, Jones & Roos (1990) defines LM as a dynamic process of change, driven by a systematic set of principles and best practices aimed at continuous improvement. LM combines the best features of both mass and craft production.

The Lean Manufacturing concept was derived from Toyota Production System (TPS). The birth of lean was in Japan within Toyota in the 1940s: The TPS was grounded in the wish to produce in a continuous flow, which was the opposite of a long production runs system; it was based around the acknowledgement that only a small part of the total time and effort to process a product added value to the end customer. This was clearly the opposite of what the Western world was doing mass production based on material resource planning (MRP) and complex computing systems that were developing alongside mass production philosophies from Henry Ford, i.e. high volume production of standardized products with minimal product switches (Melton, 2005)

Sugtogmori et al. (1977) defined the TPS with 2 main components: 1-"reduction of cost through elimination of waste". This includes building a system that will systematically eliminate waste by considering that anything other than the minimum amount of equipment, materials, parts, and workers which are undeniably essential to production are simply surplus that only raises the cost; 2- " to make full use of the workers' capabilities", which means to consider and include the employees in the process of improvement.

2.5 Background analysis

Through these background analyses we identified the potential of integration between I4.0 and LSS, and a systematic literature review will later be performed to explore this potential, and will be explained in Chapter 3, methodology.

3 METHODOLOGY

In order to attain our research objectives, the research methodology adopted was based on 5 phases, based on the design science approach, which will be explained in Section 3.1

3.1 Design Science

This research has an exploratory nature and is limited to the use of the tools in the first phases of the LSS: Define and Measure. Since the work is intended to create or adapt a few tools to deploy the strategy at the operational level, we have adopted a Design science approach (Hevner, March, Park & Ram, 2004) with a proof-of-concept to be realized in a manufacturing company in Quebec.

The Design science approach was chosen because it helps to develop and test the proposed approach. Design Science offers guidelines to ensure the quality of the research, including: the development of a conceptual framework, the definition of the relevance of the problem and the contribution of the research; verification of the rigor of the research, realizing several iterations and communicating the results of the research (Hevner et al., 2004).

Design science classifies its artifacts in 4 categories: constructs, model, method, instantiation. Constructs form the vocabulary of a domain, and are used to describe problems and their solutions. A model is a set of propositions or statements showing relationship among constructs. A method is a set of steps (an algorithm or guideline) used to perform a task. Instantiation concerns the operationalization of constructs, models, and methods (March & Smith, 1995). In this research, the artifacts are classified as model, because of its framework adaptation to I4.0, and also are classified as method, because there is a step by step instruction to deploy I4.0 strategy.

The phases of this research project are: 1) literature review; (2) development of the conceptual framework; (3) application of the conceptual framework in a manufacturing company in Quebec; (4) assessment of the conceptual framework; (5) improving the conceptual framework. These phases are described in Table 2 below.

Table 2 : Design science steps

Design science steps	**Description**	**Main expected results**
(1) development of the literature review	Identify the theoretical frameworks to drive this research, as well as the tools of the LSS and the maturity of the I4.0 models	The systematic literature review is conducted to identify the existing theoretical framework, LSS tools and maturity models.
(2) development of the conceptual framework	Development of the conceptual framework of the research and its tools	Conceptual framework development as a roadmap to deploy I4.0 strategy
(3) application of the conceptual framework	The main data collection takes the form of a mixed qualitative and quantitative study in a manufacturing company in Quebec	1 - The assessment of the maturity of the company in the I4.0, using the questionnaire of the model "IMPULS" 2-Presentation of the results to management and understanding of the strategy of the company towards the I4.0 - 3 Evaluation of a production process, in identifying its current and future state using the LSS tools
(4) evaluation of the conceptual framework	The usefulness, quality and effectiveness of the conceptual framework / tools must be demonstrated rigorously, through the good execution of the assessment methods.	In this regard, we used the approach of TAM ('Technology Acceptance Model') (Davis, 1985), which allows to assess the usefulness and ease of use of the conceptual framework and tools.
(5) improve the conceptual framework	The results of the tests must allow the improvement of the model.	Data collected about the application of the test and feedback from the company will be inputs to improve the framework and tools. This project provides only one iteration because of the restriction of time in a master's degree; However, new iterations are proposed.

3.1.1 Step 1 – Systematic Literature Review

This review was based on the methodology designed by (Conforto, Amaral & Silva, 2011), comprising three phases.

3.1.1.1 Phase 1: Inputs

This phase consists of the definition of the inputs for the literature review, as well as its planning. Table 3 below shows the phase 1 protocol.

Table 3 : Input phase for literature review (research protocol)

Phase	**I4.0 Maturity models**	**I4.0 integration with LM**
Objectives	Identify the existing I4.0 maturity models	Identify the current works about I4.0 integration with LM
Database definition	ABI /INFORM, SCOPUS, SCIENCE DIRECT. Searches were done using « title », »abstract », »keywords »	ABI/INFORM, SCOPUS, SCIENCE DIRECT. Searches were done using « title », »abstract », »keywords »
Search strings	((“Industr* 4.0” OR “Smart Manufacturing” OR “Industrial Internet of Things”) AND (“Maturity Models” OR “Readiness”))	((“Industr* 4.0” OR “Smart Manufacturing” OR “Industrial Internet of Things”) AND (“Lean Manufacturing” OR “Lean Production”))
Inclusion criteria	Maturity models that presents its dimensions, sub-dimensions, stages and questions. Articles in English language only	Works that presents practical examples of integration, linking I4.0 principles/methods with LM principles/methods. Articles in English language only.
Qualification criteria	Type of Industry, Literature Type, differentiation aspects from other models, Implementation Data	Integration type, implementation data, tools for integration
Filters	First Filter (Reading title, abstract, key words); Second filter (Reading of introduction, conclusion); Third filter (Complete reading)	First Filter (Reading title, abstract, key words); Second filter (Reading of introduction, conclusion); Third filter (Complete reading)

Source: Adapted from Conforto et al. (2011)

3.1.1.2 Phase 2: Processing

The results after performing all the steps of phase 1. Data Processing is shown in Table 4. Concerning the I4.0 maturity model, the search strings identified 30 articles (database extraction total). After duplicates removal, the results decreased to 28. After the first and second filter, the number of articles dropped to 9 and 5. Finally, after the third filter, there were 5 remaining articles. Concerning I4.0 integration with LM, the search strings identified 64 articles (database extraction total). After duplicates removal, the results decreased to 62. After the first and second filter, the number of articles dropped to 31 and 17. Finally, after the third filter, there were 11 remaining articles.

Table 4 : Systematic Literature review results

Filtering Phase	**I4.0 Maturity model Number of articles**	**I4.0 integration with LM**
ABI/Inform	15	19
Science Direct	3	2
Scopus	12	43
Database extraction total	30	64
Duplicate removal	28	62
Filter 1: Abstract, Key words, title, references	9	31
Filter 2: Reading of introduction, conclusion	7	17
Filter 3: Complete reading	5	11

3.1.1.3 Phase 3: Outputs

The outputs are displayed in item 4.2. The articles were classified for a better understanding of the research subject.

3.1.2 Step 2 – Framework development

The framework was chosen based on the systematic literature review (SLR) and will be adapted if necessary so that it can be used as a roadmap for I4.0 strategy deployment. The LSS operational tools was also chosen based on the SLR and adapted to the I4.0 context and Business Intelligence process.

3.1.3 Step 3 – Applying framework developed for data collection (proof-of-concept)

This step will define the criteria to choose the company for the application of the framework and also describes strategical and operational data collection that was based on two special tools identified by literature review step.

The company where the framework will be applied will be in an I4.0 transformation process and also will have used Lean Manufacturing methods and tools in its production process. This I4.0 transformation process should involve initial investments in the fields of smart factory and smart strategical level data collection. The person that will be interviewed should be the person responsible for operations.

This data collection of the strategy part will begin with the aid of IMPULS method, where the questionnaire of Annex 1 will be used to interview the directors of the company in person. The IMPULS method was chosen because it is the only I4.0 maturity model that has a significant number of implementations in the manufacturing industry (see Table 3 of this document).. After this interview, a report of companies´ current I4.0 maturity level was generated with the help of IMPULS online tool. Although the report shows the maturity level of all 6 IMPULS maturity levels, this research will prioritize only 2 IMPULS dimensions, smart factory and smart operations, for the following reasons: 1) time restriction in a Master's degree research; 2) These dimensions are the ones more related to the operational level of the company. After the analysis of IMPULS report, a discussion of the company I4.0 strategy in the short, medium term is made with the help of the form project charter. This discussion prioritized the company's strategy concerning the smart factory and smart operations, where some high-level actions of these strategies were documented with the desired completion dates

3.1.3.1 Operational Data collection

Concerning the operational part, the proposed VSM 4.0 tool (which will be presented later) was applied to a production line of the company. This first VSM 4.0 application is named the “current VSM 4.0”, documenting the status of each phase of the process towards the smart operation and smart factory. Besides these I4.0 measures of smart operations and smart factory, the classical VSM measures are also produced. At the same time, some improvement opportunities were registered towards the smart factory and smart operations, so that these improvements may help the company to attain the strategy registered in the project charter form. A new VSM 4.0 is then elaborated, named “VSM 4.0 future state”, with estimated new values of the classical VSM items and smart operations and/or smart factory new estimated values.

3.1.4 Step 4 – Evaluation of the conceptual framework.

In this regard, we will use the approach of Technology Acceptance Model (TAM) in order to assess the usefulness and ease of use of the proposed framework. The decision behind this validation approach is based on the methodological principles of the Information System theory called “Technology Acceptance Model”. This theory proposes that when users are presented with a new technology, two major factors influence whether they will use it or not (Davis, 1985): 1) Perceived usefulness (PU): states the degree to which users believe that using a technology would enhance their job performance; 2) Perceived ease-of-use (PEOU): refers to the degree to which users believe that using a system would be free from effort. Table 5 presents the perceived usefulness and perceived ease-of-use evaluation format employed later in this work. In this case, when possible improvements issues have been identified, we indicate those considered priority. This qualitative evaluation is discussed in Section 7.1.2 (de Santa Eulalia, 2011).

Table 5 : TAM criteria

Tool aspect	**Perceived use-fulness**	**Improvement comments**	**Perceived ease-of-use**	**Improvement comments**
Impact on I4.0 strategy deployment				
Impact of data collection and analysis				
Impact in company performance				
Impact in understanding I4.0 concepts				

3.1.5 Step 5 – Improve the conceptual framework

This step was not performed in this research, due to time constraints in this Master's degree, but future directions are proposed at the end of this document.

4 Systematic Literature Review Results

Subsection 4.1 presents a bibliometric analysis, and Subsection 4.2 provides the content analysis of all articles.

4.1 Bibliometric results

The bibliometric analysis was based upon five criteria: year of publication, journal or conference, authors, country of the principal author, and research design. Figure 3 shows the articles by publication year. Concerning I4.0 maturity models (I4.0MM) the figure shows the first year as 2014, which means that this subject is quite new, since the term I4.0 was first launched in 2011. The literature is still in its infancy, with a total of 6 articles until 2017. Regarding the industry 4.0 & lean manufacturing integration (I4.0 & LM), the first article was published in 2015, and the interest for this subject has been increasing since then.

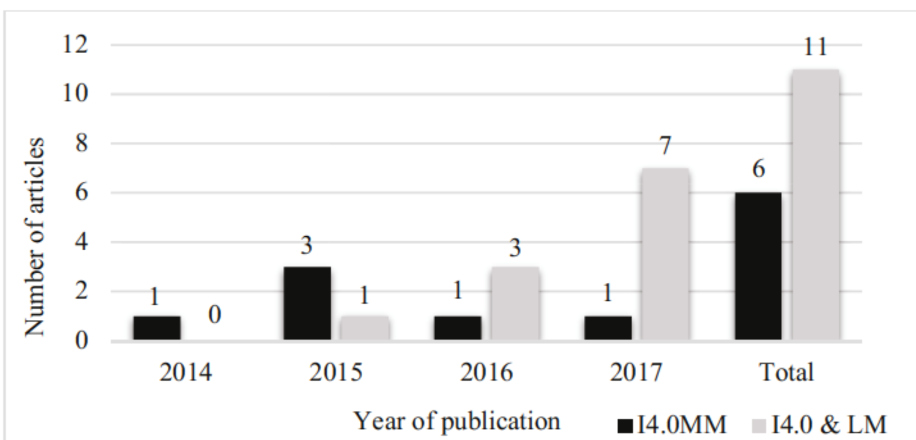

Figure 3 - Articles by publication years

Figure 4 presents the articles per periodic type. Regarding I4.0 MM, there is a predominance of white papers (4 out of 6), which denotes that this subject is still mostly covered by the grey literature rather than the scientific one. Concerning I4.0 & LM, there is a slight predominance of the conference (6 out of 11) over journals.

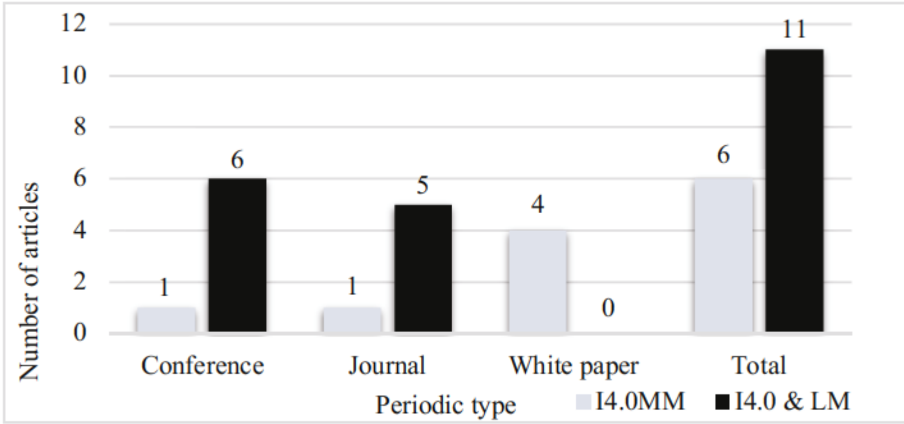

Figure 4 - Articles by periodic type

Figure 5 illustrates the number of articles by the country of the principal author, with Germany predominating, for a total of 3 out of 6 articles concerning I4.0 MM, and a total of 4 out of 11 concerning I4.0 & LM. It can also be noticed that it is in Europe where these articles are mostly written, including other countries like Italy, Croatia and Poland. Other continents have started to publish articles on this subject, such as America (USA, Brazil) and Asia (India and Turkey).

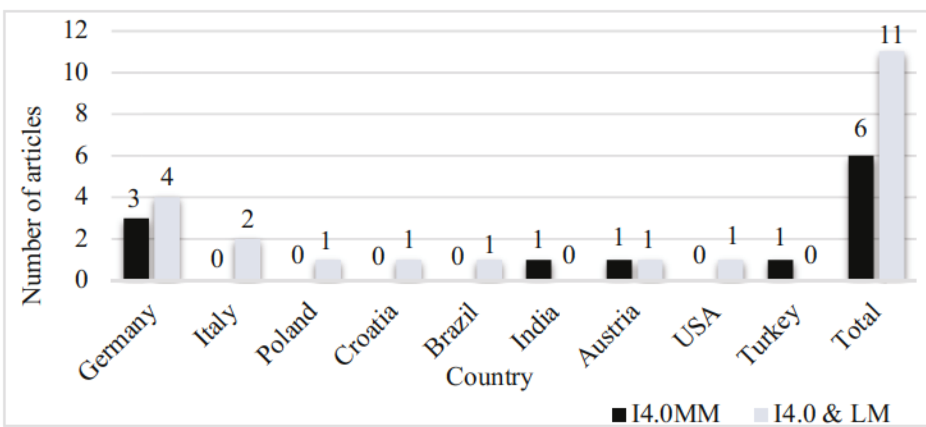

Figure 5 - Articles by country of the principal author

Figure 6 below shows the number of articles by research methodology. It is not surprising that the research strategy most used is the qualitative one, based on semi-structured interviews, because the implementation data for this subject is scarce.

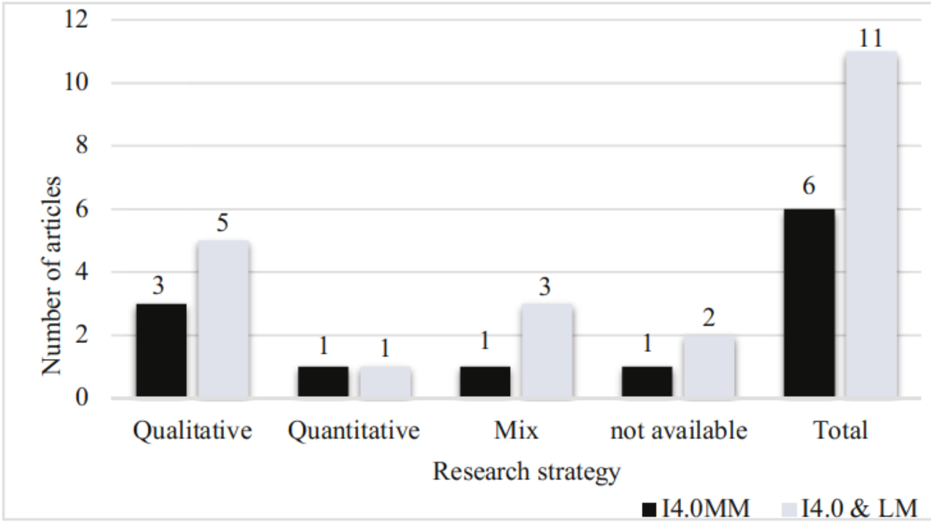

Figure 6 - Articles by research strategy

4.2 Content results

Table 6 shows the content analysis regarding I4.0 MM. Regarding the type of industry, all models were made for the manufacturing industry, except Industry 4.0/Digital Operations Self-Assessment - PWC model, which can be applied in manufacturing and other industries, like retail & consumer, financial services, etc. Concerning the employed dimensions, the model with the highest quantity is “A maturity model for assessing Industry 4.0”, with 8 dimensions, followed by the IMPULS and PWC model, with 6 dimensions each. The less detailed model regarding dimensions number is the I4.0 Reifegrad-model, with 3 dimensions. As for integration with LM, no maturity model presented this feature. Data about the implementation of these models are rare, but in the year 2015 the IMPULS provided some data about 289 companies in Germany. This tool is in evolution and there should be more data nowadays concerning the number of companies, countries, etc. (Lichtblau et al., 2015).

Table 6 : I4.0MM content Analysis

Model	Type of Industry	Dimensions number,	description	Integration with LM	Use Data
IMPULS – Industrie 4.0 Readiness. (Lichtblau et al., 2015)	Manufacturing	6	Smart factory Smart operations Smart products Data-driven services Employee Strategy	no	289 industries in Germany
Industry 4.0 / Digital Operations Self-Assessment - PWC model (Pricewaterhouse Coopers , 2015)	Several	6	Business Models, Product & Service Portfolio Market & Customer Access Value Chains & Processes IT Architecture Compliance, Legal, Risk, Security & Tax Organization & Culture	no	Not available
A maturity model for assessing I4.0 (Schumacher et al., 2016)	Manufacturing	9	Strategy Leadership Customers Products Operations Culture People Governance Technology	No.	1 industry in Austria
I 4.0 Reifegradmodell FH – (Oberösterreich, 2015)	Manufacturing	3	Data Intelligence Digital Transformation	no	Not available
I4.0-MM (Gökalp et al., 2017)	Manufacturing	5	Asset Management Data governance Application management Process transformation Organization alignment	no	Not available

Figure 7 organizes all articles by I4.0 & LM integration type. Information about this subject is still scarce, due to the low number of articles found in the literature review (11). There were 9 articles out of 11 that considered I4.0 as an enabler to LM, where I4.0 dimensions/technologies can remove some barriers related to traditional lean implementations, like high demand volatility, high product variety and reduced lot sizes. Also, we found the LM tool as an enabler to I4.0, with 1 article out of 11, where an adapted LM tool like Value Stream Map 4.0 (VSM 4.0) identifies digitalization opportunities in a process, and also analyzes waste reduction in the data/ information flow of a process. Finally, in 1 article out of 11, both I4.0 and LM are complementary to each other.

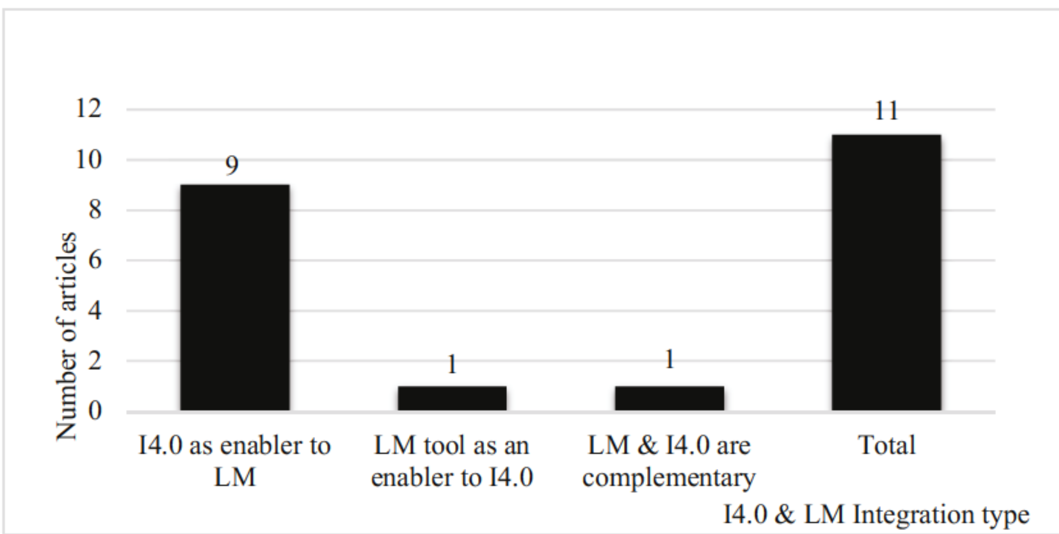

Figure 7 - Articles by I4.0 & LM integration type

Table 7 reviews the I4.0 & LM integration. Only 1 out of 11 articles presents LM tools adapted to I4.0 (column LM tools adapted to I4.0). The column I4.0 & LM integration level describes that 6 out of 11 articles give clues about the integration level, i.e. I4.0 dimensions linked to LM principles.

Table 7 : I4.0 & LM integration summary

	Authors	I4.0 & LM integration type	I4.0 & LM integration details	LM tools adapted to I4.0
1	Dombrowski et al. (2017)	I4.0 as enabler to LM	I4.0 technologies, like cloud computing, improve LM principle (waste avoidance). I4.0 process digitalization improves all LM principles, especially the standardization.	n/a
4	Jayaram et al. (2017)	LM & I4.0 are complementary to each other	LM and I4.0 are complementary to each other	n/a
5	Kolberg et al. (2015)	I4.0 as enabler to LM	I4.0 dimensions (smart operator, product, machine, planner) improves LM Principle (Just in Time, jidoka), methods (Kanban, Andon)	n/a
7	Meudt et al. (2017)	LM as enabler to I4.0	n/a	VSM 4.0
8	Lödding et al. (2017)	I4.0 as enabler to LM	I4.0 dimensions (smart operator, smart product, smart machine, smart planner, smart workstation) improves LM Principles (JIT, total quality management, Total productive maintenance, Human resources management)	n/a
9	Mrugalska et al. (2017)	I4.0 as enabler to LM	I4.0 Dimensions (smart products, smart machines, augmented operator) improve LM principles (JIT, Poka-yoke, single minute exchange die, continuous improvement, jidoka)	n/a
12	Rauch et al. (2017)	I4.0 as enabler to LM	I4.0 technologies, like cloud computing, digitalization influence LM principles such as JIT	
14	Sanders et al. (2016)	I4.0 as enabler to LM	I4.0 technologies as a solution to problems at LM dimensions	n/a
16	Tortorella et al. (2017)	I4.0 as enabler to LM	Association between LM implementation level and I4.0 technological level on company´s performance	n/a
17	Veza et al. (2016)	I4.0 as enabler to LM	Correlation between companies' performance, I4.0 and LM implementation	n/a
18	Wagner et al. (2017)	I4.0 as enabler to LM	I4.0 technologies impact on LM principles	n/a

4.3 Literature review discussion

I4.0 as an enabler to LM

LM is the foundation for I4.0 (Dombrowski et al., 2017). To analyze the interdependencies and correlations between Lean Production Systems and I4.0, 260 usage cases at companies were analyzed, concerning the application of I4.0 technologies, process related characteristics of I4.0 and principles of Lean Production. I4.0 technologies were defined as: big data, radio frequency identification (RFID), cloud computing, augmented and virtual reality, sensor/actuator, real-time data, automated guided vehicles (AGV), consumer electronics. The process-related characteristics of I4.0 were described as: horizontal and vertical integration, real-time data, transparency, flexibility, digitalization, consistency of information, monitoring, visualization, traceability and self-optimization. LM principles were defined as: standardization, zero defects, continuous flow, pull flow, continuous improvement, employee orientation and management by objectives, visual management and avoidance of waste. I4.0 process-related characteristics were described as: horizontal integration, vertical integration, real-time data, transparency, flexibility, digitalization, consistency of information, monitoring, visualization, traceability and self-optimization.

Regarding the link between I4.0 technologies and LM principles, the findings were: 84 out of 260 companies that applied the LM principle of avoidance of waste indicated the usage of cloud computing as I4.0 technology, so cloud computing was the most popular I4.0 technology for this LM principle. The zero defect LM principle indicated big data as the most used I4.0 technology, with 37 cases out of 152. Concerning the link between I4.0 process-related characteristics and LM principles, the main results were: in 89 out of 499 cases that applied the LM Standardization principle, the most-used I4.0 process was digitalization (Dombrowski et al., 2017).

Kolberg et al. (2015) and Mora et al. (2017) stated some LM limitations, such as difficulties to level capacity utilization, due to strong variation in market demand. I4.0 technologies, such as real time-data collection and analysis, and autonomous processes, can mitigate this LM limitation, levelling capacity utilization automatically. As LM started in the 1950s, it does not take into account the use of modern technologies, such as the I4.0 ones. In order to improve LM principles and methods, Kolberg et al. (2015), Mora et al. (2017) and Mrugalska et al. (2017) stated that some I4.0 dimensions can be implemented, such as: smart operator, smart product, smart machine, smart planner (Kolberg, Zühlke, Zuehlke & Zühlke, 2015). For example, the I4.0 smart operator can empower the LM methods like Kanban and Andon. Kanban is a method of labelling small production lots to get better control of raw materials, purchased parts, work-in-progress as well as of the rate, total volume and timing of production (Gravel & Price, 1988).

Smart operator helps to implement the Kanban method, because operators can get information about the remaining production cycle time via augmented reality. Andon is a visual management tool that shows the status of operations in an area and signalizes the occurrence of abnormalities (Kemmer, 2016). Within the Andon method, by which employees should be notified as soon as possible in case of a failure, the smart operator could reduce time between failure occurrence and failure notification. Equipped with smart watches, employees receive error messages and error locations close to real time. In comparison to widespread signal lamps, recognizing failures no longer depends on the location of employees.

Smart products can enable Kanban method because they contain Kanban information to control production processes. Smart machines have standardized physical and IT interfaces, suitable for sending and receiving Kanban information. It can support Andon by sending failures directly to smart operators and informing other systems for corrective action. With the smart planner, traditional Kanban systems with fixed amount of Kanban, fixed cycle times and fixed round trips for transporting goods turn into dynamic productions automatically adopting to current production programs.

Rauch et al. (2017) presented research on the I4.0 influence in LM principles in a product development environment. The findings were: 55% of respondents declared that cloud computing, one of I4.0 technologies, influences the LM principle of interdisciplinary product development processes. Digitalization, like digital workflows, influences the LM JIT principle, was the response of 45% of the respondents (Rauch, Dallasega & Matt, 2016).

Sanders et al. (2016) analyzed how I4.0 technologies and processes can contribute to LM dimensions, including supplier feedback, JIT delivery by suppliers, supplier development, customer involvement, pull production, continuous flow, setup time reduction, total productive maintenance, statistical process control and employee involvement.

One paper presented the correlation between companies in Brazil, regarding the fields of operational performance improvement, I4.0 technology levels, and LM implementation levels. The results have shown that only for companies with high operational performance improvement, there was a significant association with LM and I4.0 (Tortorella & Fettermann, 2017).

There has been research about LM and I4.0 implementation in Croatian companies. It was found that 75% of the companies do not apply LM, and that fact was detected as a main obstacle for companies to move towards I4.0, because LM implementation creates one of the foundation for I4.0 implementation, reducing waste in processes, performing standardized work, visualization of performance indicators, etc. (Veza, Mladineo & Gjeldum, 2016).

Implementation of I4.0 provides the insertion of new technologies into the current LM processes as well as the change of business processes. The influence of I4.0 technologies on LM systems was researched in 24 companies in Germany. I4.0 technologies were clustered into three Cyber Physical Productions Systems (CPPS), as follows: data acquisition and data processing, machine to machine communication (M2M) and human-machine interaction (HMI). Data acquisition and data processing use technologies such as sensors and actuators, cloud computing, big data, analytics, so that these hardware and sensors can communicate and interact with the physical world. M2M contains the technologies of vertical and horizontal integration. Vertical integration connects machines and data on different levels. Horizontal integration connects machines and data on the same level. Human-machine interaction (HMI) consists of information sharing and collaboration between machines and employees, via technologies like virtual reality and augmented reality (Wagner, Herrmann & Thiede, 2017).

LM tools as an enabler to I4.0

The Value Stream Map (VSM) is a method that allows the analysis of value added in a process chain, so that waste elimination/reduction opportunities can be identified and addressed. An adapted version of VSM, the VSM 4.0, can identify digital improvement opportunities. The analysis is also extended to identify wastes in data and information, which differs from the classical VSM, which generally only identifies wastes in the physical activities of a process. It also analyzes the collection point of data/key performance indicators (KPI), its storage media and where they are used. It provides the following metrics: data availability (DA), data usage (DU) and digitalisation rate (DR). DA stands for the % of the planned data points that are actually collected. DU means the % of the planned data points that are used for continuous improvement or decision-making. DR means the % of the data collected that is digital (Meudt et al., 2017).

4.4 Research gaps identified in the literature

The integration between I4.0 and LM was presented only at the operational side, there was no type of integration regarding the strategic side, showing how to deploy I4.0 strategy into the shop floor with the help of LM principles or tools, which is a research gap today. Another gap is that only 1 out of 11 articles demonstrated how LM adapted tools can help to identify and quantify the implementation potential of I4.0 technologies, in terms of waste reduction, quality improvement, etc.

5 THEORETICAL FRAMEWORK: LSS ADAPTED TOOLS

The adapted model of Erol et al. (2016) will serve as a comprehensive framework for the strategy of the I4.0. The adaptation that was made was to relate tools for each phase of the model, according to Figure 8, because the original framework did not have the means to make concrete and tangible the principles of I4.0 at the operational level, so the tools make the bridge between the strategic and operational level.

The first phase, envision, stands for the companies common understanding of its current maturity level regarding I4.0. The tool used for this phase is the IMPULS method and its questions are shown in Annex 1. It is appropriate, because it covers the different dimensions of industry 4.0 proposed by Schumacher, Erol & Sihn (2016) and represents several principles of I4.0 proposed by Hermann, Pentek & Otto (2016). Table 8 presents a match of these principles and the dimensions of the IMPULS to diagnose its current state in the company.

Table 8 : IMPULS dimensions and I4.0 principles

IMPULS dimensions	**I4.0 principles**
Smart products	Information transparency decentralized decisions
Smart operations	Interconnection, decentralized decisions
Smart factory	Information transparency
Data-driven services	Not applicable
Employees	Not applicable
Strategy & organization	Not applicable

The second phase, enable, means the vision for the I4.0 strategy for the long term and its road mapping. The tool adopted for this phase is the project charter, which is described later in Section 5.2. Finally, the third phase, enact, consists of the I4.0 strategy transformation in projects. The tool for this phase are the LSS-adapted tools to the I4.0 context, that are presented later in Section 5.3

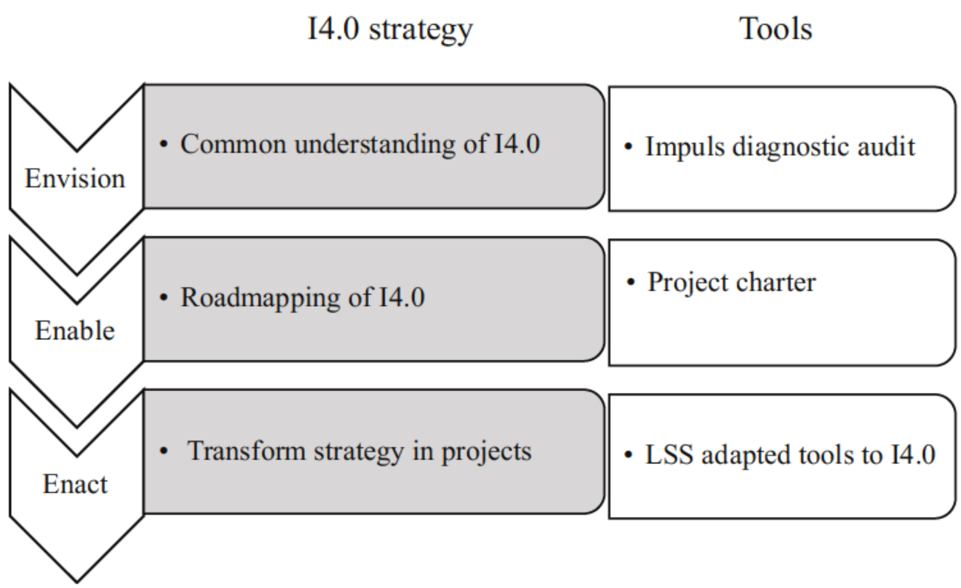

Figure 8 - I4.0 strategy framework. Adapted from Erol et al. (2016)

5.1 I4.0 Envision – IMPULS diagnostic audit

IMPULS defines six levels of maturity of the I4.0 (0-new incoming 1-beginner 2-intermediate; 3-experiment; 4-expert; 5 - top performance). The IMPULS also presents the main obstacles to achieve a higher level of maturity. The IMPULS questionnaire is shown in Annex 1.

5.2 I4.0 Enable – Project Charter

The project charter form is necessary to document the company I4.0 strategy commitment and main projects, as well as its main deadlines. This document serves as a guide to implement I4.0 projects, because it presents the I4.0 dimensions that should be prioritized. The form has two main parts according to Figure 9: Part 1 stands for the I4.0 current state, where the current company I4.0 maturity level is registered, as well as the I4.0 dimensions maturity level. This maturity levels information comes from the IMPULS report, after the company has responded to the IMPULS questionnaire. The second parts stand for the I4.0 desired future state, in terms of maturity level, and the

I4.0 dimensions that should be prioritized. The action plan to attain these future I4.0 maturity levels is also documented. The other support items of information are Current I4.0 projects/initiatives, and the VSM as-is findings and VSM future state (Pyzdek & Keller, 2010).

INDUSTRY 4.0 PROJECT CHARTER

1- I4.0 As is state

Company: Unit/Division:

Current I4.0 IMPULS Level:

IMPULS report:

2- I4.0 Future State

I40 Strategy:

Future Desired Level:

I4.0 Dimensions to be Prioritized:

Action Plan to change level

Current I4.0 projects/initiatives:

VSM as-is findings

VSM future State:

Figure 9 - I4.0 project charter, adapted from Pyzdek et al. (2010)

5.3 Enact - LSS adapted tools to I4.0

5.3.1 Classic VSM

Value Stream Mapping (VSM) aims to allow systematic identification of losses and waste in the production process. It allows representing the actions that create value and those that do not create value in the process of transformation of a product from an initial state to a final state. It also allows the detection of potential improvements (Meudt et al., 2017). Value stream mapping promotes the visualization of station cycle times, inventory buffers at intermediate stations, manpower usage, value added percentage, availability rate and cycle time. It records the entire transformation of a production line, from raw materials to finished goods. The VSM is normally recorded using an EA3 (11x17 inch) size paper. There are icons that represent the customer and its shipping frequency, the supplier and its receiving frequency, the production control and its link with suppliers and customers (Seth & Gupta, 2005).

VSM is based on 5 phases: 1) selection of a product family; 2) current state mapping; 3) future state mapping; 4) defining a working plan; 5) achieving a working plan. Some guidelines are necessary for the definition of the future state map, including the one saying that the production rate should follow customer demand ("takt time"), borrowed from the German Word "Takzzeit", which means clock interval. Continuous flow should be established whenever possible; where the continuous flow is not possible, employ the pull system (where the production is pulled according to the customer demand), which differs from the non-lean method (where production is pushed according to each station capacity, generating unnecessary inventory). Only one process, called the pacemaker or bottleneck process, should command the production of different parts, and it will set the pace for the whole value stream.

The VSM has the following advantages: The analysis of as-is state is based on the collect and analysis of numerical data and it uses a visual interface where it is easy to see the relationship between material and information flows. The analysis of the whole value chain of a product family allows seeing the inefficiencies. The delivery of a standard language for the team and the unification of lean concepts and techniques in a unique body. The VSM can be the beginning of a strategic plan for improvement (Serrano Lasa, Ochoa Laburu & de Castro Vila, 2008)

5.3.2 VSM adapted to I4.0 – VSM 4.0

According to Figure 10, the adapted VSM 4.0 has a classical part, an industry 4.0 (smart operations, smart factory), and a business intelligence (BI) part, shown in Figure 11.

The adapted VSM 4.0 is shown in Figure 10. The following sections were added into the classical VSM: smart operations, smart factory. Smart factory stands for the following sub dimensions: Equipment Infrastructure, Data Collection, Data usage. They were added to reflect the deployment of I4.0 strategy, because these dimensions are found on IMPULS method, which is the first step towards an I4.0 strategy, according to Figure 8. Once these I4.0 sections are added in the classical VSM, it is possible to check the strategy deployment on the shop floor. Table 9 shows the evaluation grid for each one of these sections.

Data collection and data usage details

Data collection and usage are shown in Figure 11, following BI process concepts. This section was adapted from Meudt et al. (2017) where the following sections were added: data quality, cost, visualization, analysis and decision. The fields are explained in Table 10. Data quality has a specific grid, detailed in Table 11, it assesses some factors that may influence data quality, such as: type of storage (paper or digital), type of recording for digital storage (semi-automated or automated), presence of quality verification for non automatic recording.

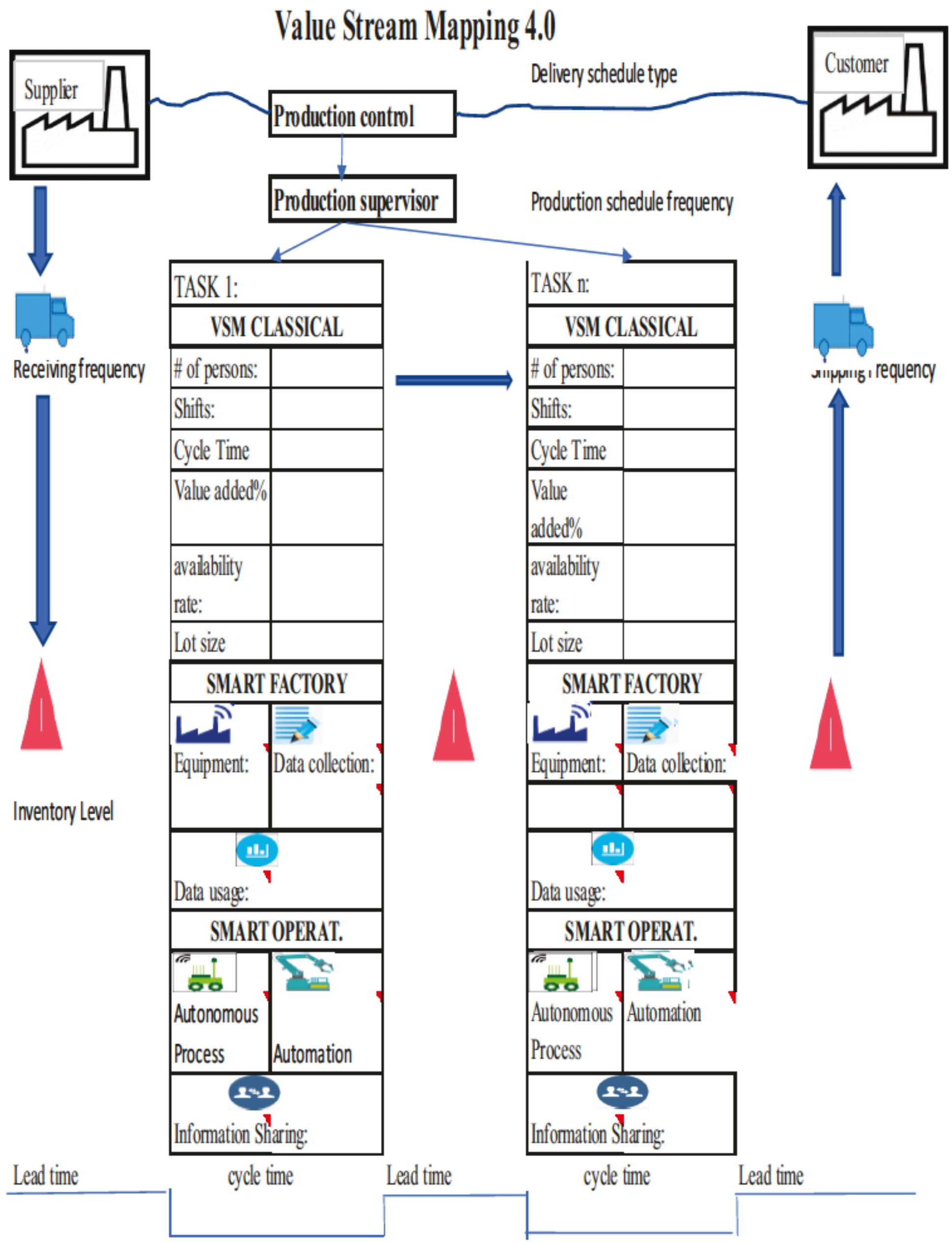

Figure 10 - VSM 4.0 – Adapted from Meudt et al. (2017)

Table 9 - IMPULS evaluation by dimension, adapted from Lichtblau et al. (2015)

IMPULS		
DIMENSION	**SUB-DIMENSION**	**VSM Action**
SMART FACTORY	Equipment infrastructure	0-Machine and system infrastructure cannot be controlled through IT, no M2M 1- Some machines can be controlled through IT, are interoperable, or have M2M capability 2- Machine and system infrastructure can be controlled to some extent through IT, is interoperable or integrated 3-Machine and system infrastructure can be controlled through IT and is partially integrated 4- Machinery can be controlled completely through IT, is partially integrated (M2M) or interoperable 5-Machines and systems can be controlled almost completely through IT and are fully integrated (M2M)
SMART FACTORY	Data collection	0 - no data is collected 1- no data is collected 2- Data is collected but for the most part manually 3- The relevant data is collected digitally in certain areas 4- Comprehensive digital data collection in multiple areas 5- Comprehensive, automated, digital data collection in all areas
SMART FACTORY	Data Usage	0 - no data available for further use 1 - no data available for further use 2- Data is used for a few select purposes (greater transparency, etc.) 3- Some data used to optimize processes (predictive analysis), 4- Data used in several areas for optimization 5- Data used in all areas for process optimization
SMART OPERATIONS	Autonomous processes	0-Autonomously guided workpieces not in use 1-Autonomously guided workpieces not in use 2-Autonomously guided workpieces not in use 3-Autonomously guided workpieces not in use 4-Experiments in test and pilot phase 5-Use in selected areas or even cross-enterprise
SMART OPERATIONS	Information sharing	0-No system-integrated information sharing 1-Beginnings of in-company, system-integrated information sharing 2-In-company information sharing partially system-integrated 3-Some in-company and beginnings of external system-integrated information 4-Predominantly in-company and partially external system-integrated information 5-Comprehensive in-company and partially external system-integrated information sharing

5.3.2.1 The BI concept inside Smart Factory

Figure 11 is inspired by the BI process and gives support to the smart factory items of data collection and data usage.

Table 10 : BI form – Fields description

Field	Description
Frequency of data collection	Frequency of data collection in %
Type of recording	Describes the way that the employee records the data: a= automated, s= semi-automated, m=manually
*Type of measures	Setup time, cycle time, availability, yield, value added, OEE, Productivity
Storage	Indicates the way the data are storage: Paper or digital
Data usage (Departments)	Describes what department uses the collected data: Shop floor, process control, quality management
Data usage (Quality)	Represents the data quality , according to the scale showed in Table 11 (1 to 5)
Data usage (Cost)	Indicates the cost to collect the data (L=Low, M= Medium, H=High
Visualiation	Represents the type of visualization: Reports ((m)anual/ (a)utomatic), Dashboards, ((m)anual/ (a)utomatic.)
Analysis	The analysis fields can be classified as descriptive, predictive or prescriptive
Decision	Can be classified as Alerts (automatic alerts generated by the dashboards), action/opinion (action or opinion taken manually by the manager) or automated action, where an automated decision is generated based upon a dashboard value

Table 11 : Data quality evaluation

Score	Description
1	Data storage on paper, no data quality verification
2	Data storage on paper, with data quality verification
3	Data storage digitally, with semi-automated recording, no data quality verification
4	Data storage digitally, with semi-automated recording, with data quality verification
5	Data storage digitally, with automated recording, no human intervention

Task:

		Product measures	setup time	cycle time	availability	yield	value added	OEE	Productivity
	Frequency for data collection								
	*Type of recording								
storage	Paper								
	Digital								
Data usage	Shopfloor Management								
	Process control								
	quality management								
	**Data quality								
	***Information Cost								
Visualis.	Reports ((m)anual/(a)utom.)								
	Dashboards ((m)anual/(a)utom.)								
Analysis	None								
	descriptive								
	predictive								
	prescriptive								
Decision	Alerts								
	Action/Opinion								
	Automated action								

*type of recording: a= automated, s= semi-automated, m=manually
**Data quality - Scale from 1 to 5, 5 is the best quality;
TBE= to be evaluated
***Information cost: L= low, m= medium, h=high

Figure 11 - BI process, Smart factory, adapted from Meudt et al. (2017)

6 APPLICATION - PROOF-OF-CONCEPT CASE

6.1 Company Profile

This section shows the results of the conceptual framework implementation, in one manufacturing company in the province of Quebec. The company profile is shown in Table 12.

Table 12 : Company profile – Case Study

Sector	Manufacturing, automotive
Number of employees	100 to 249
Revenue (2017)	10M cad to under 50M cad
Industry 4.0 current priority (2017)	Smart Products

6.2 Strategical Level - Envision - IMPULS as-is state

The IMPULS questionnaire was applied, in a semi-structured interview with the company Vice President of Innovation using the IMPULS online tool, according to Annex 1. After the IMPULS questionnaire responses, using the on-line tool, a report was generated and the results are shown in Table 12. The overall result was level 2. This score is calculated according to the formula (1):

$$O_s = 0,25 \ x \ ST_s + 0,14 \ x \ SF_s + 0,19 \ x \ SP_s + 0,14 \ x \ DS_s + 0,10 \ x \ SO_s + 0,18 \ x \ E_s \qquad (1)$$

Where:

O_s = Overall score ;

ST_s = Strategy and organization score;

SF_s = Smart factory score;

SP_s = Smart product score;

DS_s = Data driven score;

SO_s = Smart operations score;

E_s = Employee score.

Using the values of Table 13, we obtain the overall score of 2,39, which according to the IMPULS grid rounds this score to level 2:

$$2{,}39 = 0{,}25 \times 2 + 0{,}14 \times 1 + 0{,}19 \times 5 + 0{,}14 \times 3 + 0{,}10 \times 2 + 0{,}18 \times 1$$

This overall result of 2 is classified as intermediate level, and means that the company has already taken the first steps towards I4.0, like incorporating I4.0 strategy in its strategic planning, initial collection and use of production data, products with IT based add-on functionalities, etc. (Lichtblau et al., 2015).

Table 13 : IMPULS results – as-is state

Industry 4.0 dimensions	Score
Overall	2
Smart products	5
Data driven services	3
Smart operations	2
Strategy and organization	2
Smart Factory	1
Employees	1

IMPULS as-is state – Smart Products

It is remarkable that the maximum score of the company is in smart products, i.e. 5 out of 5, as indicated in Table 13. This score is a consequence of the company strategy to invest in smart products, according to question 7, Annex 1, where it is shown that the research and development department was the only one that received a large investment in the past, concerning I4.0 implementation. Level 5 means that company products use comprehensive add-on functionalities and use of collected data for various functions, according to Annex 2, smart products. Annex 1, question 18, corroborates the use of product add-on technologies, where the company uses 7 out of 8 available add-on functionalities. Annex 1, question 20, also states that the data collected by smart products are analyzed.

IMPULS as-is state – Data driven services

Data driven services had a score of 3. Although the company had services generated from smart products, integrated with their customers (Annex 1, question 19), the revenue from these services represents 5% of total revenues, which classifies the company in level 3 for data-driven services (Annex 2, data-driven services).

Impuls as-is state – Smart operations

This dimension had a score of 2. It presented information sharing along internal departments and initial external information sharing (Annex 1, question 13). The company did not have autonomous process (Annex 1, question 14). As the IT security solutions were implemented only for data storage, it classifies the smart operations in level 2 ((Annex 2, smart operations).

IMPULS as-is state – Strategy and organization

Strategy and organization had a score of 2. The company had achieved all requirements for level 1 (Annex 2, strategy and organization), like pilot initiatives in the departments of research and development and production (Annex 1, question 4), and initial I4.0 investments (Annex 1, question 7). It presented only one requirement for level 2, investments at low level (Annex 1, question 7), which was enough to classify strategy and organization as level 2.

IMPULS as-is state – Smart factory

Smart factory presented a score of 1. Because there was no M2M and machine system controlled by IT (Annex 1, question 4), the smart factory remained in level 1 (Annex 2, smart factory).

IMPULS as-is state – Employees

Employees dimension was graded 1. They presented a skill concerning future requirements for I4.0 in only one area, IT infrastructure (Annex 1, question 21), but these skills need some improvement, which let the company be classified in level 1 (Annex 2, employees).

6.3 Enable - Project charter as-is state

After the IMPULS questionnaire responses, and the analysis of IMPULS report, the company elaborated the document project charter, to document its strategy towards I4.0, according to Figure 12. The strategy was to increase the I4.0 Smart factory, from level 1 to level 2. These action plans were determined with the help of Table 9, IMPULS evaluation grid by dimension, where the requirements of each IMPULS level are shown. The next step was to perform a VSM 4.0 as-is state, following the conceptual framework Enact, so that the action plan can be updated with more details, and then the field “VSM as-is findings” can be filled in.

INDUSTRY 4.0 PROJECT CHARTER – Revison:1 **Date**: 2018-02-20

1- I4.0 As is state

Company: Manufacturing1

Current I4.0 IMPULS overall level: 2

Smart factory: 1

Smart Operations : 2

2- I4.0 Future State

I40 Strategy: Focus on smart factory and smart operations

Future Desired Level:

Smart factory: 2

Smart Operations : 2

Action Plan to change level:

Perform a VSM 4.0 as-is state (planned to 2018-03-02), to investigate the following possibilities:

data collection - collect different types of relevant data then the current ones

data analysis - begin to do predictive Analyses

Autonomous process – Investigate the feasibility

Current I4.0 projects/initiatives:

As of today, there was no further I4.0 initiative planned on Smart factory, smart operations

VSM as-is findings:

To be determined

VSM future State:

To be determined

Figure 12 - Project charter first version, adapted from Pyzdek et al. (2010)

6.4 Enact - VSM 4.0 as-is state

The VSM as-is state was performed in the production line, including the phases of machining, inspection, assembly preparation and assembly. The results are shown in Figure 13 and the business intelligence part of smart factory is shown in Figure 14 and Figure 15.

VSM 4.0 as is state, Machining + Inspection

The data about the Classic VSM was collected from a company historical data, regarding the time to manufacture a complete machine and concerning task 1: Machining + inspection. This data was not collected in real time at the company, due to time limitations (the lead time to produce their products is long, 26 weeks) and also because it is not the focus of this research, the focus being to collect I4.0 data, the Classic VSM data helps to understand the manufacturing context. It presented a value added of 66%, which means that the cycle time of the machines represented 66% of the total lead time, and 34% of the time was considered waste. The availability rate of 70% means that the machines were available to operate in 70% of the total lead time, and 30% of the total time was wasted with machine downtime, setups, etc.

VSM 4.0 as is state, Machining + Inspection – Smart factory

Concerning the I4.0 measures, smart factory, we had the following: equipment infrastructure with 0 score, because it had no machines controlled via IT or M2M capabilities . Data collection had a score of 3, according to the criteria shown in Table 9 (relevant data collected digitally in certain areas). The collection was made by the operator, on a frequency of 100% of the operations, after finishing every operation on a machine, by scanning a barcode available at each machine (type of recording was semi-automated), sending the data automatically to a manufacturing system (digital storage). The type of data collected was: setup time, cycle time, availability time; the following data types were collected on paper: quality parts and maintenance data. Figure 14 presents the details of data collection. The field data quality in Figure 14 had a score of 4 out of 5, of which 5 is the best possible quality. This score was given according to the Vice President of Operations perception, using a scale of from 1 to 5. It didn't have the maximum score, because sometimes the operators made a mistake and scanned twice after finishing an operation. The field data cost refers to the cost of obtaining this data and it has a scale of L, M, H, where L refers to low cost, M for medium cost and H for high. It was evaluated as Low for this task.

Data usage had a score of 2, which stands for: data is used for a few select purposes (greater transparency, etc.), according to Table 9. The collected data was analyzed weekly by the departments of shop floor management and quality control (Figure 14) and the data were visualized via dashboards that were generated automatically after the data collection. The analysis fields were classified as descriptive, which means that the historical data was used in the decision process, there were no predictive capabilities concerning the future behaviour of these data. Concerning the decision fields of Figure 14, there were no alerts generated by the dashboards, nor automated actions, the managers used the dashboards to help them to form their opinion, and take decisions.

VSM 4.0 as is state, Machining + Inspection – Smart operations

Regarding Smart operations, the field of autonomous process was scored as 0, because there was no evidence of this activity. Information sharing presented a score of 2, which means in company information sharing, partially system integrated, see Table 9. The company presented internal information sharing along some departments, like shop floor management, quality control, but there was no external information sharing, such as its suppliers, which prevented the company from being classified in the higher level (3) of information sharing.

VSM 4.0 as is state, assembly preparation + assembly

It presented a value added of 95%, which means that the cycle time of the machines represented 95% of the total lead time, and 5% of the time was considered waste. The availability rate of 90% means that the machines were available to operate in 90% of the total lead time, and 10% of the total time was wasted with machine downtime, setups, etc.

VSM 4.0 as-is state, assembly preparation + assembly – Smart factory

Concerning the I4.0 measures, smart factory, we had the following: equipment infrastructure with 0 score, because it had no machines controlled via IT or machine to machine communication capabilities (M2M). Data collection had a score of 3, according to the criteria shown in Table 9 (relevant data collected digitally in certain areas). The collection was made by the operator, on a frequency of 100% of the operations, after finishing every assembly preparation, by typing in a digital tablet available at each machine (type of recording was manual, due to the manual typing), sending the data automatically to a manufacturing system (digital storage). The type of data collected was: setup time, cycle time, availability time;

Figure 15 presents the details about data collection. The field data quality on Figure 15, had a score of 4 out of 5, of which 5 is the best possible quality. This score was given according to the Vice President of Operations perception, using a scale of from 1 to 5. It didn't have the maximum score, because sometimes the operators made a mistake, and scanned twice after finishing an operation. Data quality for quality parts and maintenance data was classified with a score of 2, because it is a manual data collection, paper based. The field data cost, refers to the cost of obtaining this data, and it has a scale of L, M, H, where L refers to low cost, M for medium cost and H for high. It was evaluated as Low for this task.

Data usage had a score of 2, which stands for: data is used for a few select purposes (greater transparency, etc.), according to Table 8. The collected data was analyzed weekly by the departments of shop floor management and quality control (Figure 15) and the data were visualized via dashboards that were generated automatically after the data collection. The analysis fields were classified as descriptive, which means that the historical data was used in the decision process. There were no predictive capabilities concerning the future behaviour of these data. Concerning the decision fields of Figure 15, there were no alerts generated by the dashboards, nor automated actions, the managers used the dashboards to help them to form their opinion and take decisions.

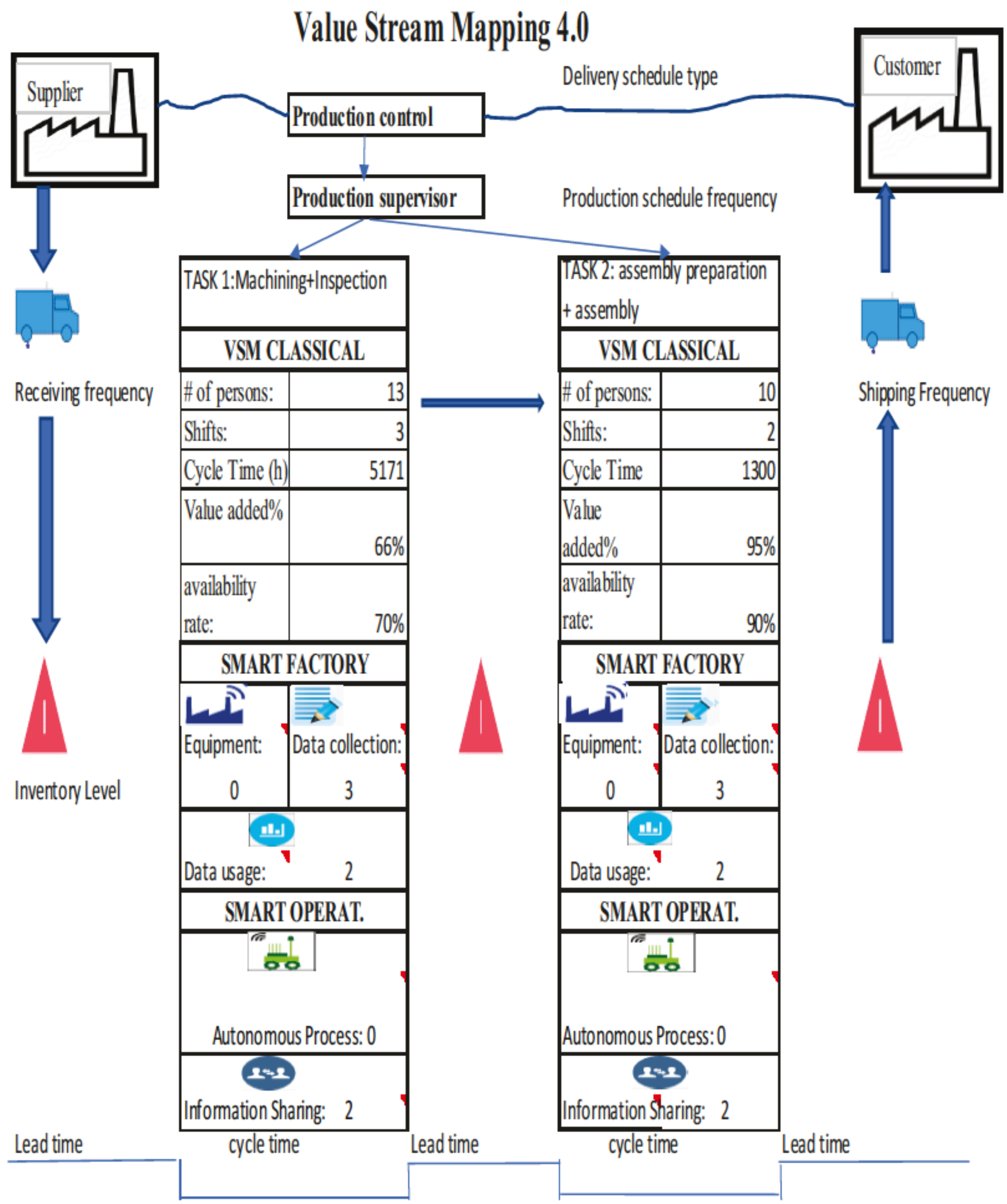

Figure 13 - VSM 4.0 as-is state (adapted from Meudt et al. (2017))

Task: machining +inspection

			setup time	cycle time	availability	Parts quality	Maintenance data	OEE	Productivity
	[+]Frequency for data collection		100%	100%	100%	100%	100%		
	*Type of recording		s	s	s	m	m		
storage	Paper					x	x		
	Digital		x	x	x				
Data usage	Shopfloor Management		x	x	x	x	x		
	Process control								
	quality management		x	x	x	x	x		
	**Data quality		4	4	4	2	2		
	***Information Cost		L	L	L	L	L		
Visualis.	Reports ((m)anual/(a)utom.)					(m)	(m)		
	Dashboards ((m)anual/(a)utom.)		(a)	(a)	(a)				
Analysis	None								
	descriptive		x	x	x	x	x		
	predictive								
	prescriptive								
Decision	Alerts								
	Action/Opinion		x	x	x	x	x		
	Automated action								

* type of recording: a= automated, s= semi-automated, m=manually

** Data quality - Scale from 1 to 5, 5 means the best quality

*** Information cost: L= low, m= medium, h= high

Figure 14 - BI as-is state, machining + inspection, adapted from Meudt et al. (2017)

Task: Assembly prep. + assembly

		Product measures	setup time	cycle time	availability	Parts Quality		OEE	Productivity
	Frequency for data collection		100%	100%	100%				
	*Type of recording		m	m	m				
storage	Paper								
	Digital		x	x	x				
usage	Shopfloor Management		x	x	x				
	Process control								
	quality management		x	x	x				
	**Data quality		4	4	4				
	***Information Cost		L	L	L				
Visualis.	Reports ((m)anual/(a)utom.)								
	Dashboards ((m)anual/(a)utom.)		(a)	(a)	(a)				
Analysis	None								
	descriptive		x	x	x				
	predictive								
	prescriptive								
Decision	Alerts								
	Action/Opinion		x	x	x				
	Automated action								

* type of recording: a= automated, s= semi-automated, m=manually

** Data quality - Scale from 1 to 5, 5 means the best quality

*** Information cost: L= low, m= medium, h= high

Figure 15 - BI as-is state, assembly prep. + assembly (adapted from Meudt et al., 2017)

6.5 VSM 4.0 future State

After the activity of the VSM 4.0 as-is state, another VSM 4.0 was performed, the future state map, where the improvement actions were proposed to deploy the I4.0 strategy documented in the project charter, according to Figure 13.

VSM 4.0 future state differences from 4.0 as-is state

The following improvements actions were recorded in the VSM 4.0 future state, according to Figure 18. The Classic VSM data of cycle time (h), value added, availability rate, were not collected because of time limitations (long lead time of several weeks to produce a product) and because they are not the focus of this research.

VSM 4.0 future state differences - Smart factory

The company chose to apply the changes only in task 1 for now, because task 1 has a larger number of machines that can bring more benefit to the company than the task 2 station. There was a change in the score of smart factory, data collection, from 3 to 4. According to Table 9, for this change from level 3 to 4 in data collection to occur, it is necessary for the company to collect more data than the current ones. Thus, the company will begin to collect quality data about the parts being manufactured, like parts defects, its root causes, and corrective actions, and also data about machine maintenance, related to its downtime, like the machine defect, time to be repaired, etc. For some parameters concerning machines operation, like feed and cut speed and others, the company has a plan to collect them in the next 12 months and, when implemented, it will change the data collection to 4.

Regarding data usage, there was a change in the score of smart factory, data usage, from 2 to 3. According to Table 9, for this change to occur from level 2 to 3 in data usage, it is necessary for the company to use data to optimize processes (predictive analysis). Therefore, the company will start to collect data from machine operation in order to use it for predictive maintenance. Another type of predictive analysis will be made, using the machine dataset for cycle time, setup time and availability in order to discover patterns and predict delays in the project. This predictive analysis is forecasted to begin in a time frame of 18 months from now.

VSM 4.0 future state differences - Smart operations

The company chose not to invest in the autonomous process and automation for now; it was decided to prioritize smart factory items, then smart operations scores remain the same. However, the company has an ongoing project concerning machine components/modules standardization, which may build a path for future automation possibilities.

VSM 4.0 future state differences - BI

The smart factory, BI, is shown on Figure 17. The following additional items will be collected: machine parameters, quality parts, maintenance data. They will be recorded with a frequency of 100%, where the operator will type the data in a digital tablet at each station, so the type of recording will be done manually (manual typing on the system). These data will be stored in a digital manner, directly on the system shown in the digital tablets.

The improvements made will change the analysis from descriptive to predictive. Regarding the decision, an improvement action will be performed in the dashboards, with the establishment of automatic alerts, whenever the data reach a pre-defined level. These alerts will be shown in the dashboards, and also will be sent automatically by e-mail to the concerned management. These improvements are forecasted to happen in a time frame of 10 months from now.

Revised Project Charter document

After the VSM 4.0 future state is made, the document project charter can be revised, with updates to the fields: action plan to change level, VSM as-is findings and VSM future state. In the action plan to change level, the detailed actions brought up by the VSM 4.0 future state are described. In the VSM fields, the scores are presented. The revised project charter is presented in Figure 18.

Re-run of IMPULS questionnaire

Although all the improvements that were documented in the VSM 4.0 future state for smart factory, data collection and data usage, they were not sufficient to change smart factory level from 1 to 2 since level 2 requires future functionalities (partially) satisfied or upgradable to some extent, according to Annex 2 smart factory. This means that equipment infrastructure has to be in level 2, which means machine and system infrastructure can be controlled to some extent through IT and it is interoperable or integrated. This was not the case in the company, where there were no machines controlled via IT and there were no plans to implement it, because it was not economically feasible. Therefore, the IMPULS level of the company in smart factory stayed at 1 and did not change.

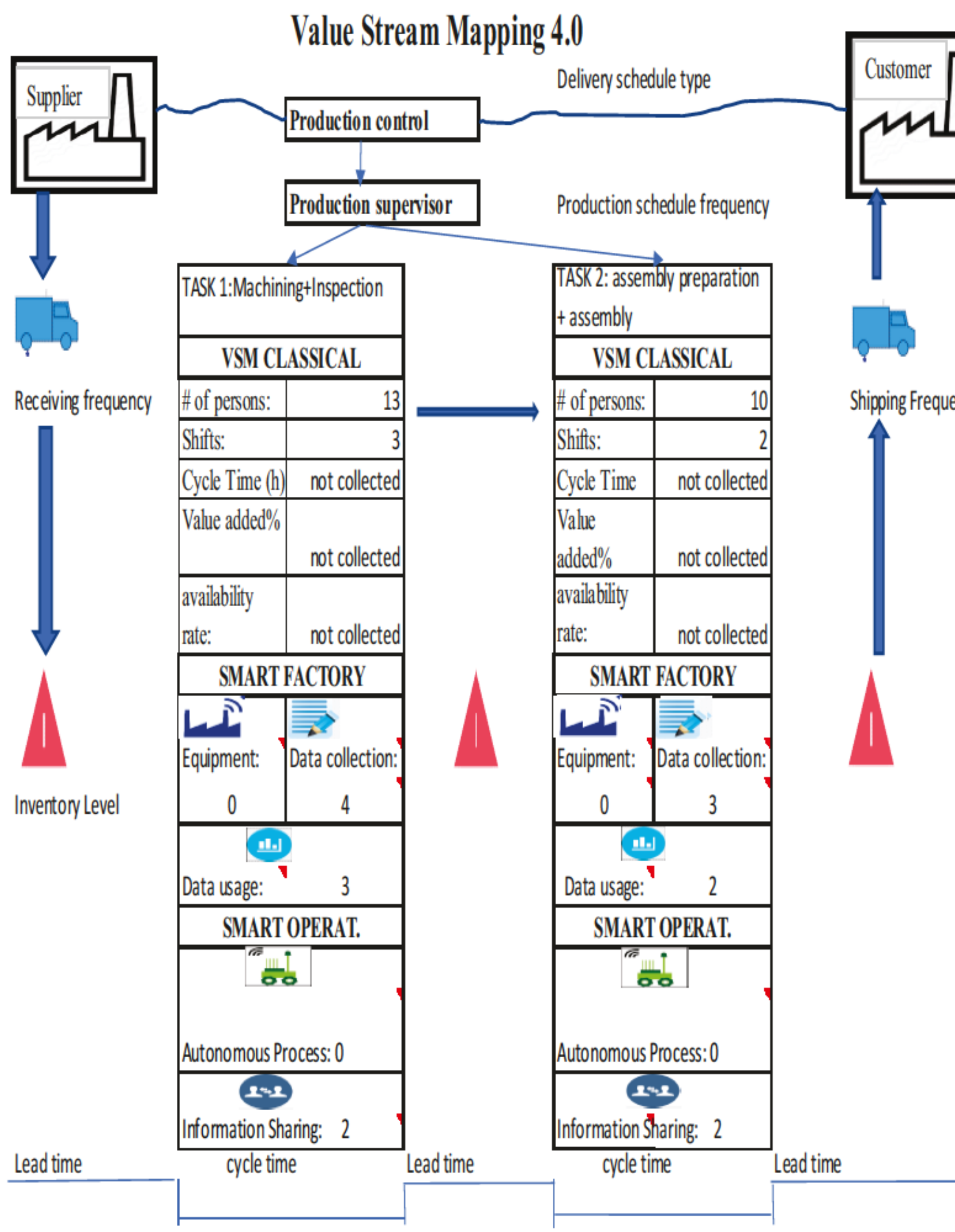

Figure 16 - VSM 4.0 future state, adapted from Meudt et al. (2017)

Task: Machining + Inspection

		machine parameters	setup time	cycle time	availability	Parts Quality	Maintenance data	OEE	Productivity
	Frequency for Recording	100%	100%	100%	100%	100%	100%		
	*Type of recording	m	m	s	s	m	m		
storage	Paper								
storage	Digital	x	x	x	x	x	x		
usage	Shopfloor management	x	x	x	x	x	x		
usage	Process control								
usage	quality management	x	x	x	x	x	x		
	**Data quality	TBE	4	4	4	TBE	TBE		
	***Information Cost	L	L	L	L	L	M		
Visualis.	Reports ((m)anual/(a)utom.)								
Visualis.	Dashboards ((m)anual/(a)utom.)	(a)	(a)	(a)	(a)	(a)	(a)		
Analysis	None								
Analysis	descriptive		X		X	X			
Analysis	predictive	X		X			X		
Analysis	prescriptive								
Decision	Alerts	X	X	X	X	X	X		
Decision	Action/Opinion								
Decision	Automated action								

* type of recording: a= automated, s= semi-automated, m=manually

** Data quality - Scale from 1 to 5, 5 means the best quality; TBE= to be evaluated

*** Information cost: L= low, m= medium, h= high

Figure 17 - BI future state, machining, adapted from Meudt et al. (2017)

INDUSTRY 4.0 PROJECT CHARTER – Revison:2 **Date**: 2018-03-20

1- I4.0 As is state

Company: Manufacturing1

Current I4.0 IMPULS overall level: 2

Smart factory: 1

Smart Operations : 2

2- I4.0 Future State

I40 Strategy: Focus on smart factory and smart operations

Future Desired Level:

Smart factory: 2

Smart Operations : 2

Action Plan to change level:

data collection - collect additional type of data: : machine parameters, quality parts, maintenance data, planned to 2091-03-20

data analysis - begin to do predictive Analyses , planned to 2019-09-20

Automation, autonomous process – After feasibility analysis, these actions were not forecasted

Current I4.0 projects/initiatives:

As of today, there was no further I4.0 initiative planned on Smart factory, smart operations

VSM as-is findings:

Smart Factory: Data collection: 3, data usage: 2, equipment infrastructure:0

Smart operations: Autonomous process: 0, information sharing: 2

VSM future State: planned to 2018-03-20

Smart Factory (For task 1 only)

Data collection: 4, data usage: 3, equipment infrastructure:0

Smart operations: Autonomous process: 0, information sharing: 2

Figure 18 - Project charter second revision, adapted from Pyzdek et al. (2010)

7 DISCUSSION

In this section, we present the research question and objectives answers, as well as the academic and managerial contributions from this research, along with the limits and research avenues

This research has the following objectives, and for each of these objectives we present the findings below:

1. identify what LSS tools can help to translate the strategic I4.0 objectives at the operational level; The LSS tools that were identified are: Project Charter, on the strategic side and VSM at the operational side. The project charter contained the I4.0 vision and strategy and made the link with the operational level, with clear objectives for smart factory and operation. The VSM assessed the smart factory and operations level of a process, showing on a visual tool to the shop floor, whether the strategic objectives of smart factory and operations are being attained.
2. check if these LSS tools need adaptation to the context of I4.0; these tools needed some adaptation, as described in item 3.
3. propose adjustments consistent with an I4.0 migration strategy, as appropriate; the Project Charter was adapted to theI4.0 context, with the fields of I4.0 as-is and future state, and the I4.0 future desired level, with its corresponding action plan to change I4.0 level. The VSM tool was adapted, inserting the I4.0 layer, becoming the VSM 4.0. The VSM 4.0 had the additional icons of smart factory and smart operations to reflect the I4.0 strategy objectives that were defined in the project charter, into concrete projects on the shop floor. The items inside the smart factory, like data collection and data usage, were detailed in the BI form.
4. assess the contribution of the LSS tools in an organizational context of transformation towards the I4.0. These contributions are assessed in item 6.6 of this document.

The research question that this study was seeking to answer is: What would the roadmap be to translate the I4.0 strategy into concrete projects on the shop floor, for companies that are in an I4.0 transformation process.

The roadmap was detailed in Section 4 of this document. The roadmap consisted of using the IMPULS diagnostic to determine the as-is state of the company towards I4.0. Afterwards, the document project charter was elaborated to register the company´s strategy towards I4.0. Therefore, the VSM 4.0 as-is state was performed in the company´s production line, to make a detailed diagnostic of I4.0 objectives in the shop floor. Thus, the VSM 4.0 future state was performed, where concrete projects were defined to improve and reach I4.0 objectives. At this moment, the document project charter was revised, with the VSM as-is and future state findings. Finally, the IMPULS diagnostic was performed again to check if the I4.0 results were achieved.

Concerning the I4.0 results, it was clear through the first IMPULS diagnostic that the company was prioritizing the smart products dimension, with a maximum score in this item of 5, compared to lower maturity levels inside its manufacturing (smart factory, 1 and smart operations, 2). The improvement projects were inside smart factory, regarding improvement of data collection, moving its storage from paper to digital for data regarding quality and equipment maintenance. There were also improvements forecasted in data usage, regarding analytics, about which they will begin to perform some predictive analysis regarding maintenance and project lead times. Even though these improvements existed regarding data collection and analysis, they were not enough to raise the level of smart factory, because there were no projects regarding autonomous processes, which is a condition, according to IMPULS method, to change smart factory level from 1 to 2.

This research presented some tools to bridge the gap regarding the I4.0 strategy deployment on the shop floor, like the IMPULS evaluation translated into strategic objectives in the project charter tool. From the operational side, the VSM 4.0 reflected these strategies on the shop floor, bringing IMPULS items inside VSM 4.0, like smart factory and smart operations. It brought value added to the literature, improving the VSM 4.0 with BI concepts like data quality, cost, visualization, analysis and decision.

7.1 Conceptual model evaluation

The conceptual model was evaluated both by the researcher and by the user, who was the company Vice President of operations, who participated in the case study interviews.

7.1.1 Conceptual model evaluation – Researcher point of view

Regarding the IMPULS models, it was demonstrated through the case study application that the questions regarding smart factory about data collection and data usage were easy to understand, and also easy to visualize in terms of improvement actions to progress to the next score for these levels. The Business Intelligence concepts, recorded in the BI as-is state and future state forms contributed to this understanding of the as-is state and future state possibilities. It was noticed that the IMPULS model was not totally aligned with the BI process concepts, because its evaluation grid presents the criteria of quantity of data collection and usage, whereas BI concepts go further and cover several other possibilities, such as grades for data analysis, like the descriptive, predictive and prescriptive.

On the subject of smart factory, the case study also presented for equipment infrastructure, some difficulties of understanding of the IMPULS evaluation grid, because there was no clear explanation of future equipment requirements regarding industry 4.0, and moreover, there is no international industry standard about this subject nowadays. It was also noticed that, depending on the size of the company and its business model, it is difficult to apply the concepts of smart operations, autonomous control and self-reacting processes, especially for companies with a low production volume and long lead time production processes, which was the case of the company studied.

7.1.2 Conceptual model evaluation – User's point of view

The conceptual model evaluation was evaluated by the company's Vice President of Operations, who participated in the interviews of VSM 4.0 and project charter as-is and future state according to the TAM criteria shown in Table 14.

It was considered that the model was useful to show the I4.0 strategy on the shop floor, in a visual language that the employees understand, like the VSM, and which is easy to use. It was perceived as an appropriate tool to do a mapping of the data collected and used in each station, and the BI forms (Figure 11) helped to understand the various concepts regarding data recording, storage, quality, cost, visualization, analysis and decision.There were improvement comments concerning the understanding of I4.0 concepts. The IMPULS evaluation grid was sometimes not easy to use, like the smart factory equipment infrastructure.

Table 14 : Conceptual model evaluation criteria

Tool aspect	**Perceived usefulness**	**Improvement comments**	**Perceived ease-of-use**
Impact in I4.0 strategy deployment	Helps to identify the strategy on the shop floor		Visual tool, easy to use
Impact of data collection and analysis	Useful to check if there is any data missing to be collected		BI form helps to identify the various aspects of data collection, usage, visualization
Impact in company performance	Useful if the appropriate improvement projects are identified		
Impact in understanding I4.0 concepts	Useful to have the view of the whole I4.0 concepts	IMPULS evaluation grid is very subjective	Sometimes IMPULS evaluation Grid is difficult to interpret, like equipment infrastructure

8 CONCLUSION

Companies today are working in a highly competitive market. The ability to understand and to integrate new technological and management concepts, like Industry 4.0, can be a valuable asset to these companies. To pave the way for Industry 4.0 transformation, it is recommended that companies apply Lean Manufacturing concepts to optimize the processes before digitally transforming them. This research presented a conceptual framework for these companies to auto-evaluate its current status regarding I4.0, and to formulate strategic objectives to progress in this field. It also provided a tool that helps the company to translate these objectives into concrete actions in the shop floor.

8.1 Academic contributions

The systematic literature review made some contributions concerning I4.0 & LM integration, showing that there was almost a consensus towards the integration type, where 9 out of 11 articles considered I4.0 as an enabler to LM. The articles presented LM as a foundation for I4.0 transformation, in the sense that before implementing I4.0 technologies, it is necessary to optimize the current processes applying LM principles, reducing or eliminating unnecessary activities or wastes, as well as standardizing the work, making the parts flow in small batches etc. It was demonstrated that I4.0 technologies can improve LM principles and remove some LM limitations, like its difficulties in responding to rapid market variation demands, and working in a market of low volumes.

The research also contributed to the literature, through the framework and tools adaptation to I4.0 context. The I4.0 strategic framework was adapted, describing practical tools for each phase. The project charter was modified to I4.0 context, in order to show I4.0 objectives and deadlines. The VSM 4.0 tool was adapted to reflect I4.0 dimensions like smart factory and operations, according to the strategic diagnostic tool

IMPULS, in order to make it easier to visualize I4.0 strategy on the shop floor. Also, the data collection and data usage were detailed in the BI process form, bringing new concepts such as data quality, cost, visualization, analysis and decision.

8.2 Managerial contribution

The managerial domain can benefit from this work, by using the presented tools to first formulate I4.0 strategy and then deploying them to operational level, defining practical projects and using a language that is common to the shop floor, a simple and visual tool, clearly identifying the as-is state and future desired state, after projects implementation.

8.3 Limits

This project had some limitations, like the sample size, because it chose one manufacturing company in Québec, Canada, as a case study. The geographical factor can influence company access power to new technologies, new management systems, etc. Another aspect is the business model, in the case study, the company had a make-to-order process, with long lead times to produce a product. In an environment of a different business model, for example, companies with high production volumes and smaller lead time production, the results and suitability of the concept model could be different. The size of the company, could be another factor that could influence the fit of the model, i.e. small companies have less capital to invest in new technologies, such as automation, machine to machine communication, etc. Concerning the number of adapted LSS tools to the I4.0 context, it was limited, with only two adaptations, project charter and VSM, so this could be another factor that may influence the fit of this model.

Although this research presented interesting results regarding the use of a framework to deploy I4.0 strategy, there is still a need to further discuss and validate the research findings. Therefore, we recommend the use of a larger number of companies/employees in future works, with different sizes of companies, business models, and geographical locations.

8.4 Avenues of research

There are possible avenues of research concerning the subject of I4.0 strategy deployment. This project emphasised the deployment of I4.0 strategy regarding only two I4.0 dimensions, smart factory and smart operations, so there might be future studies concerning the deployment of the other 4 dimensions of I4.0 (Strategy and organization, employees, smart products, data-driven services). Concerning the VSM 4.0, it could be verified if it could be applied at the operational level, concerning these four I4.0 dimensions.

As for the I4.0 maturity model IMPULS, it could be adapted to better fit to small and medium enterprises (SME), maybe by splitting the smart factory dimension in data collection/usage and machine to machine communication (M2M), because it's easier for SME´S to implement data collection/usage than M2M . Another aspect that could be improved at IMPULS would be a dimension related to Lean Manufacturing, because the literature review has shown that Lean Manufacturing is the foundation for I4.0

A possible future study would be to apply Lean Manufacturing tools, like the VSM, to measure the potential of I4.0 implementation in terms of waste reduction, and as a consequence, to measure its productivity gains. Another subject to be investigated would be to measure the impact of I4.0 implementation in quality improvement, using and maybe adapting other tools like the failure mode and effects analysis (FMEA) to the I4.0 context. Another aspect of I4.0 that could be further studied is the horizontal integration with suppliers in order to determine what the impact would be of I4.0 deployment into the supply chain, in terms of supplier delivery, quality and cost.

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ANNEXES

ANNEX 1 – IMPULS QUESTIONNAIRE RESPONSES

		Mechanical engineering	Manufacturing
1	Which category best describes your company?		X

		Up to 19 employees	20 to 99 employees	100 to 249 employees	250 to 499 employees	500 or more employees
2	Please estimate the size of your company's domestic workforce.			X		

		Under 1 million euros	1 million to under 10 million euros	10 million to under 50 million euros	50 million to under 100 million euros	100 million to under 250 million euros	250 million to under 500 million euros	500 million euros or	Not specified
3	Please estimate your 2014 revenues.			X					

Strategy and organization

		No strategy exists	Pilot initiatives launched	Strategy in development	Strategy formulated	Strategy in implementation	Strategy implemented
4	How would you describe the implementation status of your Industry 4.0 strategy?		X				

		Yes, we have a system of indicators that we consider appropriate	Yes, we have a system of indicators that gives us some orientation	No, our approach is not yet that clearly defined
5	Do you use indicators to track the implementation status of your Industry 4.0 strategy?			X

		Sensor technology	Mobile end devices	RFID	Real-time location systems	Big data to store and evaluate real-time data	Cloud technologies as scalable IT infrastructure	Embedded IT systems	M2M communications
6	Which technologies do you use in your company?		X	X	X	X	X	X	

7	In which parts of your company have you invested in the implementation of Industry 4.0 in the past two years, and what are your plans for the future?

	Investments in the past 2 years				Investments in the next 5 years			
	Large	Medium	Small	None	Large	Medium	Small	None
Research and development	X					X		
Production/ manufacturing				X			X	
Purchasing			X					X
Logistics			X					X
Sales		X					X	
Service		X				X		
IT			X			X		

		IT	Production Technology	Product Development	Services	Centralized, in integrative management	Do not have
8	In which areas does your company have systematic technology and innovation management?		X	X	X	X	X

Smart factory

9	How would you evaluate your equipment infrastructure when it comes to the following functionalities?

	No, not available	Yes, to some extent	Yes, completely
Machines/systems can be controlled through IT	X		
M2M: machine-to-machine communications	X		
Interoperability: integration and collaboration with other machines/systems possible		X	

10	How would you evaluate the adaptability of your equipment infrastructure when it comes to the following functionalities?			
	Not relevant	Relevant, but not upgradable	Upgradable	High, because functionality already available
M2M: machine-to-machine communications	X			
Interoperability: integration and collaboration with other machines/systems possible			X	

		Yes, all	Yes, some	No
11	The digitization of factories makes it possible to create a digital model of the factory. Are you already collecting machine and process data during production?		X	

12	Which of the following systems do you use? Does the system have an interface to the leading system?			
	In use		Interface to leading system	
	Yes	No	Yes	No
MES – manufacturing execution system		X		X
ERP – enterprise resource planning	X			X
PLM – product lifecycle management		X		X
PDM – product data management		X		X
PPS – production planning system		X		X
PDA – production data acquisition	X			X
MDC – machine data collection		X		X
CAD – computer-aided design	X			X
SCM – supply chain management		X		X

Smart operations

13	Where have you integrated cross-departmental information sharing into your system? Distinguish between enterprise-wide (internal) and cross-enterprise (external) information sharing.			
	Internally between departments		Externally with customers and/or suppliers	
	Yes	No	Yes	No
Research and development	X		X	
Production/manufacturing	X			X
Purchasing	X			X
Logistics	X			X
Sales	X			X
Finance/accounting	X			X
Service	X			X
IT	X			X
Nowhere		X		X

		Yes, cross-enterprise	Yes, but only in selected areas	Yes, but only in the test and pilot phase	No
14	The vision of Industry 4.0 is a workpiece that guides itself autonomously through production. Does your company already have use cases in which the workpiece guides itself autonomously through production?				X

		No in-house IT department (service provider used)	Central IT department	Local IT departments in each area (production, product development, etc.)	IT experts attached to each department
15	How is your IT organized?			X	

16	How far along are you with your IT security solutions?			
	Solution implemented	Solution in progress	Solution planned	Not relevant for us
Security in internal data storage	X			
Security of data through cloud services		X		
Security of communications for in-house data exchange			X	
Security of communications for data exchange with business partners			X	

17	Are you already using cloud services?		
	Yes	No, but we're planning to	No
Cloud-based software			X
For data analysis			X
For data storage	X		

Smart products

18	Does your company offer products equipped with the following add-on functionalities based on information and communications technology?	
	Yes	No
Product memory	X	
Self-reporting	X	
Integration	X	
Localization	X	
Assistance systems	X	
Monitoring	X	
Object information	X	
Automatic identification		X

Data driven services

		Yes, and we are integrated with our customers	Yes, but without integration with our customers	No
19	The process data gathered in production and in the usage phase enable new services. Do you offer such services?	X		
		Yes	No – we collect the data but do not analyze it	No – we do not collect data in the usage phase
20	Do you analyze the data you collect from the usage phase?	X		

Employees

21	How do you assess the skills of your employees when it comes to the future requirements under Industry 4.0?			
	Not relevant	Non-existent	Existent, but inadequate	Adequate
IT infrastructure			X	
Automation technology				X
Data analytics		X		
Data security / communications security		X		
Development or application of assistance systems		X		
Collaboration software		X		
Non-technical skills such as systems thinking and process understanding			X	

ANNEX 2 – IMPULS EVALUATION GRID

SMART PRODUCTS

REQUIREMENTS	SCORE
Products feature comprehensive add-on functionalities. Comprehensive use of collected data for various functions	5
Products feature add-on functionalities in different areas. Targeted use of collected data for certain functions	4
Products have multiple, interconnected add-on functionalities. Some of collected data used for analysis	3
Products have first add-on functionalities. Data collected but not analyzed/used	2
Products have first signs of add-on functionalities	1
No requirements met	0

DATA DRIVEN SERVICES

REQUIREMENTS	SCORE
Data-driven services through customer integration. Revenues generated from services (>10%) . High usage rate of data (>50% of collected data)	5
Data-driven services through customer integration. Revenues generated from services (<10%). Use of data (20%–50% of collected data)	4
Data-driven services, but without customer integration. Low revenue generated from services (<7.5%). Use of data (20%–50% of collected data)	3
Data-driven services, but without customer integration. Low revenue generated from services (<2.5%). Low use of data from usage phase (<20% of collected data)	2
Data-driven services, but without customer integration. Initial revenue generated from services (<1%)	1
Outsider. No requirements me	0

SMART OPERATIONS

REQUIREMENTS	SCORE
Complete system-integrated information sharing. Autonomous control and self-reacting processes implemented	5
Comprehensive IT security and cloud solutions implemented. Far-reaching system-integrated information sharing. Testing of autonomous control and self-reacting processes. Far-reaching IT security and cloud solutions in use	4
Some system-integrated information sharing. IT security solutions partially implemented. Initial solutions for cloud-based software, data storage, data analytics	3
Internal information sharing partially implemented. Multiple IT security solutions planned or initial solutions in development	2
First steps toward internal, system-integrated information sharing. Initial IT security solutions planned	1
Outsider. No requirements met	0

STRATEGY AND ORGANIZATION

REQUIREMENTS	SCORE
Strategy implemented and regularly reviewed. Enterprise-wide I4.0 investments . Uniform, enterprise-wide innovation management established	5
Strategy in implementation and sporadically reviewed. I4.0 investments in multiple areas . Innovation management established in multiple departments	4
I4.0 strategy formulated. I4.0 investments in a few areas. Innovation management in isolated areas	3
I4.0 strategy developed and system of indicators defined. I4.0 investments at a low level	2
Pilot initiatives in the departments. Initial I4.0 investments	1
No requirements have been met	0

SMART FACTORY

REQUIREMENTS	SCORE
Equipment infrastructure already satisfies future functionalities. All data collected and used . Comprehensive IT system support of processes	5
Current equipment infrastructure satisfies requirements or is upgradable. Most data collected, some data used. Comprehensive IT support of processes (system-integrated)	4
Future functionalities (partially) satisfied or fully upgradable. Relevant data digitally collected and used in some areas . IT systems support processes and linked through interfaces	3
Future functionalities (partially) satisfied or upgradable to some extent. Data is collected (but largely manually) and used for some activities. Some areas of the company supported by IT systems and integrated	2
Current equipment infrastructure satisfies some of future requirements. Main business process supported by IT system	1
No requirements met	0

EMPLOYEES

REQUIREMENTS	SCORE
All skills available in several relevant areas	5
Employees have adequate skill levels in several relevant areas	4
Employees have adequate skill levels in some relevant areas	3
Employees have low skill levels in few relevant areas	2
Employees have low skill levels in one relevant area	1
No requirements met	0

ETHIC COMMITTEE APPROVAL

UNIVERSITÉ DE SHERBROOKE

Sherbrooke, le 19 décembre 2017

M. Pablo Ernesto De Paiva Pereira
ÉCOLE DE GESTION (études)
Université de Sherbrooke

N/Réf. 2017-1632/Ernesto De Paiva Pereira

Objet : Approbation finale de votre projet de recherche

Monsieur,

Le Comité d'éthique de la recherche – Lettres et sciences humaines a reçu les clarifications ou les modifications demandées concernant votre projet de recherche intitulé **« Déploiment de la stratégie 4.0 à l'aide du modèle IMPULS et des outils du Lean Six Sigma »**.

Les documents suivants ont été analysés :

- Formulaire de réponse aux conditions (F20-1563)
- Projet de recherche (Proposition de recherche-v1 26-11-17.docx) [date : 26 novembre 2017, version : 1]
- Outil de collecte des données (Guide d'entrevue-Pablo-26-11-17.docx) [date : 26 novembre 2017, version : 1]
- Recrutement (Invitation Letter 17-12-2017.doc) [date : 17 décembre 2017, version : 1]
- Formulaire d'information et de consentement (Consent_form_17-12-2017_PabloP.docx) [date : 18 décembre 2017, version : 2]

Le comité a le plaisir de vous informer que votre projet de recherche a été **approuvé.**

Cette approbation étant **valide jusqu'au 19 décembre 2018**, il est de votre responsabilité de remplir le formulaire de suivi (formulaire F5-LSH) que nous vous ferons parvenir annuellement. Il est également de votre responsabilité d'aviser le comité de toute modification au projet de recherche (formulaire F4-LSH) ou de la fin de votre projet (formulaire F6-LSH). Ces deux derniers formulaires sont disponibles dans Nagano.

Le comité vous remercie d'avoir soumis votre demande d'approbation à son attention et vous souhaite, Monsieur, le plus grand succès dans la réalisation de cette recherche.

Marie-Claude Desjardins
Présidente du CÉR - Lettres et sciences humaines
Professeure
Faculté de droit

c. c. Vice-décanat à la recherche
Directeur ou directrice de recherche (le cas échéant)
Service d'appui à la recherche, à l'innovation et à la création (le cas échéant)

LETTER OF ACCEPTANCE FROM PARTICIPANTS (MODEL)

UNIVERSITÉ DE SHERBROOKE

INFORMATION AND CONSENT FORM

You are invited to participate in a research study. This document describes the study procedures. Feel free to ask questions about any words or paragraphs you do not understand. To take part in the study, you must sign the consent section at the end of this document; a signed and dated copy will be returned to you. Please take all the time you need to make your decision.

Research Study Title

Industry 4.0 - from strategic maturity models to lean six sigma operational deployment

Researcher Responsible for the Research Study

Pablo Ernesto de Paiva Pereira, Master degree student, Business Administration , Business Intelligence concentration (pablo.ernesto.de.paiva.pereira@usherbrooke.ca), (819 212 5310), under the direction of professors Elaine Mosconi (Elaine.Mosconi@usherbrooke.ca) and Luis Antonio de Santa Eulalia (L.Santa-Eulalia@USherbrooke.ca), all three from Information systems and Management quantitative methods department (SIMQG) , management School, Sherbrooke University.

Purpose of the Research Study

The purpose of this study is to deploy the Industry 4.0 strategy using IMPULS model and Lean Six Sigma tools. IMPULS is a diagnostic tool that determine the company´s current maturity level towards industry 4.0. The Lean Six Sigma tools will show the company´s current value added for a particular process, before and after Industry 4.0 implementation. This project has the goal to identify the current organization Industry 4.0 maturity level, with the IMPULS model, and also to identify the organization strategy towards Industry 4.0. Thus, this strategy will be deployed at a production and supply chain department, with the help of Lean Six Sigma tools, that will map the current value added for a process, before and after industry 4.0 deployment.

Description of the Research Procedures

Your participation in this project will be required for a 1 hour and 30 minutes interview. This interview will take place at the location that suits you, according to your availability. You will have to answer questions about the current state of your process as well as the current state of Industry 4.0 implementation. This interview will have its audio recorded.

Potential Benefits

You will get no direct benefit to participate in this research project. However, your participation will help to better understand the impact of the industry 4.0 principles application into your business processes.

Potential Risks

Your participation in the research should not have any risk, and the only inconvenient would be to give 1h30 of your time. You can ask to take a break or continue the interview at a time that suits you.

Voluntary Participation and the Right to Withdraw

Your participation in this research project is voluntary. Therefore, you may refuse to participate. You may also withdraw from the project at any time, without giving any reason, by informing a member of the research team.

If you withdraw from the study, do you ask that the audio/video or written documents pertaining to you be destroyed?

Yes ☐ No ☐ Participant's initials______________

In this eventuality, the researcher will validate your preferences regarding data destruction.

Compensation

You will not receive financial compensation for participating in this research study.

Confidentiality

During your participation in this study, the researcher responsible and the research team will collect and record information about you in a study file. They will only collect information required to meet the scientific goals of the study.

Your search folder can include information such as your name, your position in the company, your seniority at this position, audio recordings, as well as the answers of the interview which will be conducted as part of the research project

All the information collected during the research project will remain confidential to the extent provided by law. You will only be identified by a code number. The researcher responsible for this study will keep the key to the code linking your name to your study file.

The study data will be stored for 5 years by the researcher responsible for this study for research purposes as described in this information and consent form.

The data may be published or shared during scientific meetings; however, it will not be possible to identify you.

For monitoring and control, your study file may be examined by a person mandated by regulatory authorities, or the Research Ethics Board. All these individuals and organizations adhere to policies on confidentiality.

You have the right to consult your study file in order to verify the information gathered, and to have it corrected if necessary. You may also ask a copy of the research results to the researcher responsible for this study, by phone or e-mail, see section “Contact Information” below to obtain the researcher coordinates.

Contact Information

If you have questions or if you have a problem you think may be related to your participation in this research study, or if you would like to withdraw, you may communicate with the researcher responsible of this research study or with someone on the research team at the following number:

Pablo Ernesto de Paiva Pereira (819) 212-5310
Elaine Mosconi (819) 821-8000 extention 63397
Luis Antonio de Santa-Eulalia (819) 821-8000 extention 65042

Approval of the Research Ethics Board

The Research Ethics Board of the Un;09oiversité de Sherbrooke (CÉR Lettres et sciences humaines) approved this research and is responsible for the monitoring of the study. For any question concerning your rights as a research participant taking part in this study, or if you have comments, or wish to file a complaint, you may communicate with the Research Ethics Board at the following phone number 819-821-8000 (or toll free at 1-800-267-8337) extension 62644, or by email at cer_lsh@USherbrooke.ca.

Signature of the Participant

I have reviewed the information and consent form. Both the research study and the information and consent form were explained to me. My questions were answered, and I was given sufficient time to make a decision. After reflection, I consent to participate in this research study in accordance with the conditions stated above.

I authorize the researcher responsible of this research study to communicate with me directly to ask if I am interested in participating in other research.

Yes ☐ No ☐

AND I authorize the researcher also to:

Use of audio recording for scientific presentations; Yes ☐ No ☐

Name of participant Signature
Date

Commitment of the Researcher Responsible of the Research Study

I certify that this information and consent form were explained to the research participant, and that the questions the participant had were answered.

I undertake, together with the research team, to respect what was agreed upon in the information and consent form, and to give a signed and dated copy of this form to the research participant.

Name of the Researcher Responsible Signature
Date